This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

600044816T

Alexr. Cuninghame Esqre.

1996 e 777/2

AN

ELEMENTARY TREATISE

ON

NATURAL PHILOSOPHY.

TRANSLATED FROM THE FRENCH OF

M. R.-J. HAÜY,

PROFESSOR OF MINERALOGY AT THE MUSEUM OF
NATURAL HISTORY,
&c. &c. &c.

BY OLINTHUS GREGORY, A.M.

OF THE ROYAL MILITARY ACADEMY, WOOLWICH.

VOL. II.

WITH NOTES BY THE TRANSLATOR.

> ——He who enlarges his curiosity after the works of nature, demonstrably multiplies his inlets to happiness. JOHNSON.

LONDON:
PRINTED FOR GEORGE KEARSLEY, FLEET-STREET.
1807.

BODLEIAN
P
29 NOV 1962
LIBRARY

CONTENTS OF THIS VOLUME.

3. Galvanic Electricity .... Page 1
    Origin of Galvanic Electricity 3
    Theory of Volta 12
    Experiments made with the Pile 25
    Different Substances that may be used in forming a Pile 32
    Electric Fishes 37
    Chemical Effects of Galvanic Electricity 44
VI. MAGNETISM 58
1. General Principles of the Theory of Magnetism 60
2. Magnetic Attractions and Repulsions 73
3. Communication of Magnetism 91
4. Magnetism of the Terrestrial Globe 105
5. Magnetism of Iron Mines 131
VII. LIGHT 138
1. Nature and Propagation of Light 141
2. Reflection and Refraction of Light 154
3. Decomposed Light, or Colours 185
    Colours considered in Light 186
    The Rainbow 213
    Colours considered in Bodies 226
    Relations between Light and Heat 254
4. Natural Vision 260
    Structure of the Eye 261
    Manner in which Vision is effected 265
    Optical Illusions 277
5. Vision aided by Art 292
    Effects of regularly reflected Light on Vision 293
    Plane Mirrors 294
    Concave Mirrors 301
    Convex Mirrors 313
    Effects of refracted Light in regard to Vision 316
    Simple Refraction in Media terminated by Plane Faces 319
    Double Refraction 325
    Vision by means of a single Glass terminated by curvilinear Surfaces 348
    Vision aided by Instruments composed of several Glasses 365
    Concise Description of some particular Dioptrical Instruments 385

AN

ELEMENTARY TREATISE

OF

NATURAL PHILOSOPHY.

Theory of Electricity continued.

Galvanic Electricity.

461. ELECTRICITY, enriched by the labours of so many distinguished philosophers, had apparently arrived at that stage in its progress where nothing of importance is wanting to a science, and nothing left for those who might pursue it hereafter but the hope of confirming the discoveries of their predecessors, or of giving to truths, already brought to light, additional clearness. The many researches which had been set on foot to diversify the results of experiment, were seemingly exhausted, and the theory itself appeared to be capable of no further extension, unless, perhaps, by a nicer precision in the application of its already well-established principles. While the science was thus tending, as it were, to a state of repose, the convulsive motions observed by Galvani in the muscles of a frog when placed in combination with metallic

bodies, attracted the attention, and called forth the astonishment, of philosophers; for the appearances were such as to confound their ideas of the mechanism producing them. In attempting to explain these appearances, electricity however was first resorted to; and from that period every mind was directed to this new branch of physics. A variety of experiments were made, or rather, experiments similar in their nature were accumulated; and the phenomena, confined at first in their action to the animal economy, passed afterward into the department of chemistry, where, from their mode of decomposing water, many of the learned were led to doubt if the electric fluid were the real agent.

As the discussion advanced the doubts increased, when Volta, residing in the same Italy which had given birth to this new species of science, discovered the true principle of its theory, in a fact equally remarkable for its simplicity and fecundity; all the appearances which had been observed deriving their explanation from the contact merely of two substances of different natures. The doctrine of this celebrated man, spreading first through other countries, was not known in France till he came himself to explain it in person to the National Institute. The sitting of that day will long be remembered, in which he was received with so much interest by a hero, whom the learned are as proud of beholding among them, as are armies of seeing him at their head, and the reception was followed by a mark of distinction that enhanced the glory attached to the discovery itself *.

---

* In the sitting of the Mathematical and Philosophical Class of the National Institute, held 16 Brumaire, year 9, it was proposed by the first consul, after a memoir had been read by Volta, in which he gave an account of his discovery, that a gold medal should be decreed to this philosopher; and, on 11 Frimaire following, the class unanimously adopted the recom-

In treating this subject, we shall first relate the appearances which gave rise to the electricity called *galvanic:* we shall next explain the theory by means of which Volta succeeded in accounting for those appearances: we shall then proceed to other phenomena, belonging, like the first, to the animal economy, but produced by the spontaneous motion of certain fish, of which the most celebrated is the torpedo; and, lastly, we shall consider galvanic electricity as it is connected with chemistry by the decomposition of water.

Origin of Galvanic Electricity.

462. The first traces of this species of electricity are found in the account which Sultzer published in 1767, of an experiment, that is now well known. He took two pieces of different metals, such as silver and lead. Of these he placed one on the upper surface of the tongue, and the other underneath the tongue, the pieces projecting beyond the tip of that organ. He then inclined the two metals toward each other by their projecting extremities, till they met; and at the

---

mendation of a committee nominated for the purpose, which was, to present to Volta the medal of the National Institute, in gold, as a testimony of the satisfaction of the class, for the admirable discovery with which he had enriched the theory of electricity, and as a proof of their gratitude for his having imparted it to them. In the sitting of 26 Prairial, year 10, the minister of the interior, Chaptal, communicated to the same class a letter, in which the chief consul signified his intention of founding a prize medal, of 3000 francs, for the best discovery that should be made in every year on the Galvanic fluid; and, as a further encouragement, the sum of 60,000 francs to whoever, by his experiments and discoveries, should benefit electricity and Galvanism in the same degree in which those sciences had been benefited by Franklin and Volta, the class to be the judge. The programma on the subject of these prizes, drawn up by a new committee, was read at a public sitting of the Institute, 17 Messidor, in the same year.

instant of contact he experienced a taste, which he compares to what sulphate of iron produces. Hence he infers, that the junction of the two metals occasions in one of them or in both conjointly a vibration of their particles, which vibration, necessarily acting upon the nerves of the tongue, causes the sensation we have mentioned. It not unfrequently happens, that those who make the experiment are affected by a kind of light, that appears to pass before their eyes.

463. The phenomenon we have related, though similar in its nature to those belonging to the new branch of electricity, was unaccompanied at the time by any useful inferences: nor was it till the year 1789, that another fact, obtained by chance, gave to the mind sufficient impulse to induce it to enter a career, in which so many interesting results awaited it. A medical student at Bologna, in dissecting a live mouse, which he held tight in his hand, felt, as he touched one of the nerves with his scalpel, a commotion similar to what is produced by electricity *. This fact, which was rumoured over all Italy, gave rise to a variety of conjectures as to the nature of the agent occasioning it, which many philosophers supposed to be the nervous fluid, or, which they considered as the same thing, the electric fluid.

464. Shortly after, a new phenomenon presented itself, and in a manner equally unexpected, in the house of Galvani, anatomical professor in the same city. On a table, on which was an electrical machine, some frogs were placed, which had been skinned in order to make soup. A pupil at the table took it into his head to apply the point of a scalpel to the crural nerves of one of these animals, and the muscles of the frog were instantly in strong convulsions. Another

---

* Essai sur l'Histoire générale des Sciences, &c. by J. B. Biot, p. 19.

pupil did the same to another frog, and the same effect followed. A third conceived, that he had observed the convulsions take place at the precise moment that a spark was drawn from the conductor of the machine. Galvani, whose attention had been otherwise employed, on being informed of what had passed, repeated the experiment, sometimes with the electric spark and the scalpel together, sometimes with the electric spark alone, and sometimes with the scalpel alone, and he found the contractions not increased by the scalpel, and that the spark was sufficient to excite them *. That the frog, not being insulated, but within the sphere of action of the machine, should acquire resinous electricity, while the machine was at work, was readily understood; but, as to the sudden return of vitreous fluid in the body of the frog, on the application of a spark from the conductor, it was an effect similar to what is known by the appellation of the *returning stroke* (448).

Galvani varied the experiment several ways: he made use of the electrophorus and other apparatus; he tried even the action produced by the electricity of lightning: and in every instance in which the means employed were calculated to put in motion a certain portion of the electric fluid, the effects were analogous.

465. Hitherto this philosopher had perplexed himself in vain to derive some new and valuable truth from phenomena, in which his profoundly scientific mind had been able to perceive no results but what appertained to common electricity. All his attempts were ineffectual, or at least tended only to prove the extreme susceptibility of cold-blooded animals relative to the electric action, and whatever might be curious

---

* Aloysii Galvani, de viribus electricit. in motu musculari commentar. p. 2.

here, was interesting only to physiology. One day, as he held a frog suspended by the spinal marrow to a brass hook, it occurred to him to press the hook against the iron railings of a balcony in which he was standing, and in doing this frequently he perceived more than once the muscles of the frog to contract; but he hardly dared to flatter himself on these favourable indications, conceiving them to arise from the electricity of the atmosphere *. Having however carried the frog into a room of which the windows were shut, he placed it on a plate of iron, and on pressing the hook to which the frog was suspended against this plate, he found the contractions repeated. A number of similar experiments enabled him to discard every extraneous circumstance, and to reduce the apparatus to its true limits, by ascribing the phenomena to a communication between the nerves and muscles of a frog, established by means of a metallic arc.

466. Galvani had remarked, that when this arc consisted of one metal only, there were either no contractions, or very slight ones; and that an arc composed of two different metals was necessary to render them strong and durable †. Another observation, equally

467. Let us now enter a little more into detail respecting the results obtained by Galvani, adding those of other philosophers who have engaged in the same experiments. The general object of these experiments is to establish, by means of a conductor, ordinarily composed of several different metals, a communication between two points of the animal, taken in the same set of nervous or muscular organs. To the part of these organs which is situated between the points of contact, the name of *metallic arc* has been given; and the metallic substances, by means of which these points are brought into communication, have been called the *excitatory arc.*

468. The organs which have been preferred for the subjects of experiment are the crural nerves and the muscles of the same part in which the nerves are distributed. If, for example, a crural nerve having been laid bare, a sheet or coating of lead be placed underneath this nerve, and a coating of silver under the thigh on the corresponding side, and the communication between the lead and the silver be established by means of a copper exciter, the crural muscles will experience, at the moment of contact, a strong contraction, which will shew itself by a convulsive motion both of the thigh and leg.

469. If one of these coatings or supports be placed at the extremity, and the other on the middle, of the same nerve, the double contact of the excitatory arc will equally produce convulsions in the same thigh and leg.

470. If the frog be reclothed in its skin, and, after being fixed to a table, a coating of lead be placed on the belly, and another of silver on the pelvis of the animal, the same convulsive movements will still take place, from the double contact of the excitatory arc; but they will be much weaker.

471. One of the supports or coatings may be omitted, for instance that of the nerve, and the nerve, in its bare state, be placed in contact with only one of the extremities, while the other extremity touches the coating of silver placed underneath the muscle: and the convulsions will be the same as in the instance of the two supports.

472. Lastly, convulsions may further be excited by placing the nerve and muscle on pieces of the same metal, and then causing the two pieces to approach one another till they meet: but the commotions in this case are less manifest, are always slight, and, if the frogs be weak or fatigued, are wholly imperceptible.

In a report to the Mathematical and Physical Class of the National Institute, drawn up by the celebrated Halle, in the name of a committee appointed to examine and verify the phenomena of Galvanism, are a number of admirable experiments of this kind, executed with great accuracy and knowledge of the subject.

As the theory of Volta was not known at that period, it may not be uninteresting to enter more nature: and here the slightest shades, such indeed as we might be led to consider as of trivial importance, are sufficient to govern the results.

Valli, who may be regarded as the successor of Galvani, in the study of this new branch of electricity, had observed, that when the two plates of metal with which the organs of the frog had been armed were of plumber's lead, an excitatory arc of the same lead produced no effect: but if assayer's lead, which is always much purer, were substituted for one of the coatings only, though the exciter and the other coating were both of plumber's lead, the convulsions were apparent. To ascertain a difference between two metals, in other respects the same, Halle tried the experiment of simply rubbing one such piece of metal against another of a different kind: as thus, he placed under the nerve a plate of silver, that had not been touched by any other metal, and under the muscle another plate of silver, that had been previously rubbed with copper, which he so placed that the rubbed part should be in contact with the organ; and on bringing the two plates together, a sensible effect was produced. In another experiment, he combined a plate of pure silver with another that had $\frac{1}{10}$ alloy of a different metal, and the convulsions took place. The following facts are also deserving of attention. One of the coatings being of silver and the other of lead, the experiment succeeded with a leaden exciter; but it failed, when, the two coatings being silver, a copper exciter was used. Hence it followed, that any difference in the metals forming the excitatory arc, gave to that arc a very decided influence on the phenomena. But care was to be taken not to employ supports perfectly similar, even when the exciter was of a different metal. We shall soon see, that these effects, which it appeared so difficult to comprehend, were so nearly allied to the true principle of the theory, that it would be difficult to fix upon experiments better adapted to illustrate that principle, and to exhibit its interesting applications.

474. Let us now consider in what manner the cause of the phenomena we have described was at first understood. Galvani made them depend on what he called the *electrical nervous fluid*, and he conceived that the convulsions which the frog experienced, like the commotion excited by the Leyden phial, were caused by the re-establishment of equilibrium between two contrary electricities, the positive and the negative. And, as he had sometimes observed, that an arc consisting of one metal only would act upon the frog, it appeared to him not at all natural to suppose this single metal to be the seat of the two electricities, and he therefore conceived there was no alternative but to place them in the animal itself *.

Galvani afterward endeavoured to ascertain, whether one of these electricities resided in the muscle, and the other in the nerve, or whether they existed simultaneously in each of the two organs. After trying in vain to resolve this question by decisive experiments, he this discharge, analogous to what takes place in the Leyden experiment, produced the commotion [*].

475. Valli also adopted the concurring influence of the two different electricities in the phenomena of muscular contractions, with this difference, that he considered the interior of the muscles as electrised negatively, and the exterior as being in the positive state [†].

476. Volta declared himself at first in favour of this double electricity inherent in the animal, but conceived, that it acted in a different manner. This celebrated naturalist took a Leyden phial very slightly charged, and, having placed the hook of this instrument in contact with the nerves of a frog, he made the exterior furniture communicate with the muscles. In this state of the experiment he thought it evident, that the frog received impressions; whereas when the bottle was presented in a contrary way to the two organs, the animal appeared insensible. Hence he was led to conclude, that the nerves were the seat of negative, and the muscles of positive, electricity [‡]. Galvani, informed of this explanation, thought it so plausible that he adopted it, declaring, notwithstanding, that, in his opinion, it still left many difficulties to be solved [§]. But science had reserved for Volta a triumph more worthy of him.

477. One of the persons who has attacked Galvani's theory with most success is the learned Psaff, professor at Kiel. He proved, that so far from the organs of the frog bearing an exact comparison with the Leyden phial, there was a great difference between them.

---

[*] De viribus electricit. p. 40. et seq.

[†] Histoire de Electricité, vol. I. p. 58.

[‡] See Carminati's letter to Galvani, inserted in the commentary before cited, p. 67, &c.

[§] See Galvani's answer, at the end of the same work.

Among other experiments, he cited that in which the two coatings being applied to the nerve, the contractions appeared; though, in this case, the excitatory arc which produced the discharge rested, by its extremities, on the conductor of the pretended electrical machine. This observation, as will readily be seen, struck with equal force at all the modes of explaining the phenomenon, that had yet been proposed.

Theory of Volta.

478. In the first experiments undertaken by Galvani, the effects were ascribed to the influence of common electricity on the organs of a frog. This influence he soon discarded, and referred all to a combination of these same organs and a metallic arc. At that time nothing appeared so simple as this apparatus. But the moment was not arrived when Volta was to announce to philosophers, that metals only were requisite to display the true ground of the theory. We shall attempt to develope the principles of this celebrated naturalist, as he has himself communicated them to the National Institute.

480. If two different metals, insulated, and possessing only their natural electric fluid, be brought into contact, there will be formed in them, in consequence of this combination, two opposite kinds of electricity, so that, when they are separated afterward, one will exhibit signs of vitreous electricity, and the other of resinous electricity. Suppose, for instance, two discs to be applied to each other, one, *z*, of zinc, the other, *c*, of copper (fig. 55, pl. IX.), attached, by the middle of the surfaces not in contact, to two glass cylinders, *df*, *a b*, which the operator holds in his hands by their extremities, to keep the two discs insulated. In this case the zinc will acquire vitreous electricity, and the copper resinous electricity. This may be verified by means of the condenser (fig. 56), which we have already described (443). Having separated the two discs, let that of zinc be placed on the knob *g*, and touch at the same time with the other some indifferent object to restore it to its natural state. Let this operation be several times repeated, to accumulate in the collecting plate the small quantities of vitreous fluid which the zinc acquires every time the two discs are applied to each other. If the upper plate, *a b*, be afterward taken away, the straws of the electrometer will recede from each other, and the application of a stick of Spanish wax electrified by friction will evince a vitreous electricity in the straws, by determining them to approach again. If we begin the experiment anew, and substitute the copper disc in place of the zinc, by bringing it in contact with the knob *g*, after every application of the two discs, we shall find the electricity of the straws to be resinous.

481. To facilitate the explanation of the phenomena, we shall represent the sum of the two kinds of electricity, the vitreous and resinous, one belonging to the zinc, and the other to the copper, by unity.

This sum, equally divided between the two discs, will give ½ for the quantity of fluid of each; and if we use the negative sign to distinguish the fraction indicating the resinous electricity, the state of the zinc will be expressed by +½, and that of the copper by −½. We shall presently see, that, from certain circumstances, the absolute quantities of fluid may vary in the two metals: but the difference 1 between the state of the two discs remains always the same.

In thus expressing the state of the two discs, we suppose them to be insulated. But let us conceive, at the very moment they are so, a communication to be established between the disc of copper and the surrounding bodies: this disc will then tend to regain from the earth a quantity of vitreous electricity sufficient to neutralise its resinous electricity; and its new state will accordingly be represented by zero. But if the zinc, the state of which was +½, were to experience at the same time no change, the difference in the state of the two discs would simply be ½: but, from what has been said, it ought to be unit: the zinc therefore, that this condition may obtain, will acquire from the ground a new portion of vitreous fluid equal to what it possessed before; and thus, the state of the copper being still zero, that of the zinc will be represented by unit.

If, on the other hand, the zinc disc were to be placed in combination with the surrounding bodies, its state would then become zero, and that of the copper disc would be —1, as will readily be conceived.

482. Let us now introduce into the apparatus bodies moistened with water, and see what will be the result. According to Volta, when a body of this kind is placed between two metals, its sole effect, at least as far as is perceptible, is to transmit the fluid from one metal to

the other; and the distribution of the fluid takes place then as in ordinary instances; that is to say, if the metals are similar in form and of equal surfaces, there will be the same equality in their portions of fluid, after the communication.

There are thus two cases of equilibrium: one of contact, which exacts a difference of state measured invariably by *one* between metals of a different nature; the other of distance, by the intervention of a humid body, which requires, other circumstances being equal, that the metals be in the same state of electricity.

483. The following experiments exhibit in a very perspicuous manner the two instances of equilibrium. Take a metallic plate consisting of two pieces, copper and zinc, soldered together endwise: of this plate hold the copper extremity in the hand, and touch with the zinc extremity the knob *g* of the collecting plate, which is of copper. If the noninsulated plate be then taken away, the straws of the electrometer will shew no sign of electricity. For the state of the copper held between the fingers being zero, since that metal communicates with the surrounding bodies, the state of the zinc will be 1; and as the same difference ought to exist between the zinc and the collecting plate, the state of that will also be zero: whence it follows that the apparatus will have undergone no change.

484. Let us now suppose paper wetted with water to be introduced between the zinc and the collecting plate; that plate will then become charged with vitreous electricity. For, that the two equilibriums may exist, it is necessary that the state of the copper extremity held between the fingers be always zero, the state of the zinc always 1, and that that of the collecting plate, supposed to have the same dimensions as the zinc, be also represented by unit; and it is further

evident, that the electricity of this plate ought to be vitreous, like that of the zinc.

485. The manner in which Volta conceived the electricity to be produced, which takes place on two metals being brought into contact, is a little different from what we have represented. This celebrated naturalist appears to admit of an active force impelling into the zinc a portion of the electric fluid residing in the copper; and hence it is, that the first is found electrised positively, and the other negatively. In the experiment (482) in which a piece of zinc soldered to a piece of copper held between the fingers, is placed in immediate contact with the collecting plate of the condenser, the collecting plate remains in its natural state, because the zinc is in contact with copper at both ends: from which it follows, that there are two equal forces, which, acting contrary ways, destroy each other *. We have thought proper to follow the same plan here, which we observed in treating of electricity produced by friction or heat; that is, to confine ourselves to a simple elucidation of facts, without entering into the consideration of the motive force, which seems not to be yet well understood.

486. We now deem ourselves competent to explain the effects of the apparatus known by the name of *Volta's pile*, and, in doing this, we shall take for our guide the most methodical and luminous work that has hitherto appeared on the subject, which is a report made by Biot, to the Mathematical and Physical Class of the National Institute, in the name of a committee of twelve members chosen from that class. The pile is composed of discs of two different metals, for example, of copper and zinc, placed flatwise one on the other by pairs, with a piece of wetted paste-

---

* Journal de Phys. Vendemaire, year 10, p. 212.

board or cloth between every pair, as is represented in *figure* 57, where the letter *c* shews the discs of copper, *z* the discs of zinc, and *h* the humid conductors. Every pair of discs is considered as forming one of the elements of the pile.

487. That we may proceed with the greater simplicity, let us first consider the pile as insulated; and suppose that we have begun to construct it by placing only the first pair, *c* 1, *z* 2, on the insulator, the copper disc being the under one. From what has been said, it is clear that the state of the copper disc will be —½, and that of the zinc +½. Let us now place above the disc *z* a humid conductor, *h*, and above this conductor a copper disc, *c* 3. That the condition of the equilibrium of distance may be fulfilled, it would suffice that the zinc *z* 2 should cede to the copper *c* 3 half its fluid; and then, the state of the copper *c* 3 being always —½, that of the zinc *z* 2 would be ¼, and that of the copper *c* 3 also ¼. But in that case the difference between the first two discs would be only ¾, whereas it ought to be equal to unit. A new distribution of fluid will therefore be established between the three bodies, by means of which the state of the copper *c* 1 will become —⅔; that of the zinc *z* 2 will be —⅔+1 or +⅓; and that of the copper *c* 3 also +⅓, which answers to the conditions of the equilibrium.

If we add a fourth disc, *z* 4, it must necessarily have a unit more than the copper *c* 3, and this will occasion a further change in the relative quantities of the lower discs; so that we shall have —1 for the copper *c* 1, 0 for the zinc *z* 2, 0 for the copper *c* 3, and 1 for the zinc *z* 4.

By pursuing the same chain of reasoning, it will be easy to ascertain the electric states of all the different parts of the pile, whatever may be the number of discs. The quantities of vitreous electricity and those of resinous electricity will form two arithmetical progressions, in each of which the difference between any two consecutive terms will be unit.

If we suppose the number of discs to be even, we shall have the state of the first *c* 1, by dividing that number by 4, and giving the negative sign to the result. Thus in the pile represented in the figure, which consists of 12 discs, the state of the first is $-\frac{12}{4}$ or -3; which gives successively for the different pairs $-3-2, -2-1, -1+0, 0+1, +1+2, +2+3$. In this instance the sum of the two progressions will always be zero; the lower disc which is copper, and the upper disc which is zinc, will be in two equal and opposite states of electricity; and it will be the same with any two discs taken at an equal distance from the extremities. Also, previous to the passage of the resinous electricity into the vitreous, the action will become evanescent; so that there will be two discs in the natural state, which will be those in the middle of the pile.

If the number of discs be odd, we shall find the state of the first *c* 1, by taking the fourth of the number, with the negative sign, and adding to the result unit divided by four times the same number. Suppose the number of discs to be 7; the state of the first will be $-\frac{7}{4}+\frac{1}{28}$ or $-\frac{12}{7}$. So that we shall have successively for the different discs $-\frac{12}{7}, -\frac{5}{7}, -\frac{5}{7}, +\frac{2}{7}, +\frac{2}{7}, +\frac{9}{7}, +\frac{9}{7}$. In every case of this kind also, the sum total is zero.

488. Let us now suppose a communication to be established between the lower extremity of the pile and the earth below it. The first disc, *c* 1, will then tend to place itself in equilibrium with the surrounding bodies, and to resume its natural state; which cannot be accomplished without the other discs changing their state also, in such manner that the dif-

ference in that of any pair shall still be unit, and there shall be an equality between the two discs belonging to the same humid conductor. Hence it is easily seen, that the state of the different discs will be successively 0 for *c* 1, 1 for *z* 2, 1 for *c* 3, 2 for *z* 4, 2 for *c* 5, 3 for *c* 6, &c.; from which it follows, that the states of every species of metal will form an arithmetical progression, of which the first term will be zero for the copper, and unit for the zinc, and in which the difference between two consecutive terms will also be unit.

In the same instance, the sum of the terms of the two progressions united, will be expressed by the square of the number of either kind of discs, supposing the total of both kinds to be even. Thus in the pile represented by the figure, containing six discs of each kind of metal, the sum of the terms, or, which amounts to the same thing, the charge of the pile, has 36 for its expression. Hence it results, that, *cæteris paribus*, the phenomena depending on the quantity of electricity accumulated in the pile, increase more rapidly than those which depend on the quantity diffused over the upper disc. For instance, let two discs be added to the twelve composing the pile we are considering, and the change will be represented by 49, making a difference with the preceding pile of 13; while the state of the upper disc will be expressed by 7, of which the difference from that of the other pile is simply equal to unit.

The law we have announced relative to the different states of the discs succeeding each other in the pile, is the simplest that can be imagined; but it is extremely probable, that experiments of greater precision than those which have hitherto been made to ascertain it, would subject it to new modifications. It may even be presumed, that there are other agencies here, the influence of which, though weaker than that of metals, will deserve appreciating, if we would obtain a rigorous result; which will require all the resources of the most skilful physical science, combined with the acutest powers of analysis.

489. To comprehend still more completely the difference existing between the insulated pile, and that which is not insulated, let us compare them with each other as to their effect in charging the condenser. If we place the upper disc of an insulated pile in contact with the collecting plate of that instrument, the plate will draw off a part of the electricity of the pile, so that the portions of fluid in the different discs will be in a state of variation till the equilibrium be re-established. But the charge of the condenser will be limited from the circumstance even of the insulation, which prevents the pile from having more than its natural quantity of fluid, it being then unable to draw any from the surrounding bodies. Let us suppose, on the other hand, the pile to communicate with the receptacle by its base. In proportion as it shall yield its fluid to the collecting plate, it will repair its loss at the expense of the common reservoir; so that the tension of its upper disc will remain the same, and the condenser gradually charge itself with a quantity of fluid proportionate to its capacity and condensing power. Hence we see, that in the latter case the charge of the condenser, other circumstances being equal, will be perceptibly stronger than if the pile were insulated.

490. We have said (487) that, the pile being insulated and the number of discs even, there will be always two of them in the natural state, and that these two will occupy the middle of the pile. This last circumstance does not take place when the upper disc of the pile communicates with the condenser: the position of the point, at which the electricity is at zero,

varying then according to the condensing force and capacity of the instrument. For, that the equilibrium may be established, the charge of the condenser, added to the portions of vitreous fluid diffused through the discs situated between the instrument and the point zero, must constitute a sum equal to the combined quantities of resinous fluid contained in the discs included between zero and the insulator. Now, in the first place, it is easy to conceive, that in general the action of the condenser tends to raise the point zero above its first position. Also, in proportion as condensers capable of being more strongly charged are used, the point zero approaches continually nearer to the upper disc, or, which is the same thing, the number of discs electrised vitreously diminishes, while the number of those which are electrised resinously goes on increasing. Therefore, if we suppose the force of the condenser to be infinite, it will absorb all the vitreous electricity of the pile, so that zero will correspond with the upper disc, while the rest of the pile will be in the resinous state. This case is that of a pile insulated at bottom, whose upper disc, which is zinc, communicates with the earth below; and this, having an immense capacity, in comparison with that of the pile, performs here the function of a condenser whose force would be infinite.

491. All the results we have stated tend to prove, that the progressive increase of electric density, which regularly takes place in the different discs, from the base to the summit in a non-insulated pile, and from the middle to the extremities in an insulated one, depend on the intervention of humid conductors. Let us imagine a non-insulated pile, composed simply of metallic elements placed immediately one above the other. The effect of the first element will be regularly repeated from the base to the summit without any increase; so

that if the pile begins as usual with a disc of copper, the electric state of the different elements will be represented by $0+1, 0+1, 0+1$, &c. If, on the contrary, the pile be insulated, the series will become $-\frac{1}{2}+\frac{1}{2}, -\frac{1}{2}+\frac{1}{2}, -\frac{1}{2}+\frac{1}{2}$, &c. And thus nothing would be gained in either hypothesis by augmenting the number of elements, or adding to the height of the pile *.

492. Some philosophers have adopted a different mode of constructing the pile from what we have represented. In ours the discs and humid conductors were arranged in the following order, from the bottom to the top: copper, zinc, humidity; copper, zinc, humidity; &c. the pile terminating with a pair of discs, copper and zinc, that have no intervening conductor. The other pile was arranged thus: zinc, humidity, copper; zinc, humidity, copper, &c. with a single disc of copper on the last humid conductor. These two modes of forming the pile have given rise to various disputes among the learned, some maintaining, that the true element of the pile was a pair of discs, copper and zinc, followed by a humid conductor; while others were of opinion, that the arrangement constituting the element of the pile was zinc, humidity, and copper. From the principles we have laid down, the question may easily be solved. In the second method of arranging the pile, the disc of zinc, serving as the base, is considered as forming a part of the common reservoir, and the true pile as commencing at the first disc of copper that is in contact with a disc of zinc. On the other part, the disc of copper stationed alone on the top of the pile can have no other function than that of simply sharing,

---

* De l'Electricité dité Galvanique, by Volta; Annales de Chimie, 30 Frimaire, year 10, p. 250.

by the intervention of the humid conductor that precedes it, the fluid of the zinc which is in contact with the same conductor. Hence it is, that if a wire be placed in communication with the zinc commencing the pile, and another in communication with the copper terminating it, the first wire will be electrised resinously and the second vitreously; so that this pile will appear to produce effects directly the reverse of what is produced by the other. But all this will be reconciled, if we distinguish the points at which the wires are placed in contact, from those which constitute the true limits of the pile.

493. Among the different bodies that have been chosen for electrical experiments, previous to the discovery of Galvanism, the tourmalin (454) appears to bear the strongest analogy to an insulated pile, at least relative to the distribution of the two species of electricity.. In the tourmalin, as in the pile, the action of the two electricities diminishes gradually from the extremities to a certain term, where it is reduced to zero. Further, it is easy to conceive that if a pile be divided into several portions each composed of a certain number of elements, and these different portions be insulated, they will instantly become complete piles, and their halves be solicited by contrary electricities, precisely as is the case with detached fragments of a tourmalin. As far however as the present state of our knowledge will enable us to judge, there is in several respects a striking difference between the two bodies. In the electrisation of the pile, each fluid transmits itself from one disc to the other by the mediation of a humid conductor: on the contrary, when the tourmalin becomes electrised, each fluid remains, after its disengagement, in the same molecule in which it was previous to the state of combination (458). The electric densities too of the pile decrease slowly from the

extremities to the middle, where they vanish; while in the tourmalin they diminish rapidly, so that the points at which they are reduced to zero approach more or less near to the extremities. Notwithstanding these differences, a committee, formed of several members of the National Institute, have judged, that a comparison of the Voltaic pile with mineral substances electrical by heat, was worthy the serious attention of naturalists *.

494. Sometimes, instead of the pile, the apparatus termed a *couronne de tasses* (corona of cups) has been substituted. It consists of a series of glasses filled to a certain height with water, and made to communicate with each other by means of metallic arcs, which have a plate of zinc soldered to one of their extremities, and a plate of copper to the other. These conductors are so arranged that the copper extremity of one is immerged in the water contained in the first glass, and the zinc extremity of the same in the water of the next glass, and so on through the whole series. There will accordingly be in every glass a plate of copper and a plate of zinc, belonging to the corresponding conductors, and having an interval between them. And thus the succession of metals and humid conductors is the same as in the pile.

495. From the preceding statements it is manifest, that the theory of the celebrated philosopher of Pavia wholly depends on the phenomenon, unknown till that time, of an electricity, not produced in any of the ordinary ways, either by friction, or communication, or heat, but by the simple contact of two metals. If any trace of this subject could be found among the ancients, like one of those rays of light which sometimes

---

* See the Report to the Mathematical and Physical Class of the National Institute, on the prize founded by the first consul, p. 3.

precedes the most brilliant discoveries, but which sparkles for an instant and disappears, it would be in the little which Newton has written on electricity; a science which was then scarcely born. This great man, after remarking that the attractions produced by gravity and the magnetic and electrical virtues so manifestly operate at a distance that they have been perceptible even to men of the commonest capacity, adds, that perhaps there are also attractions restricted within so narrow a space as to have escaped hitherto all observation, and that perhaps electrical attraction in particular operates at extremely small distances, without requiring to be excited by friction *.

Different Experiments made with the Pile.

496. The electric action which took place on the mutual contact of metals, in the experiments on the frog, was extremely trifling in itself; and what especially contributed to render its effects perceptible was the extreme irritability of the organs that were the subject of it. This same action transferred to the pile, in which it increases by multiplying itself, is rendered capable of producing, by its sole energy, a number of phenomena analogous to those of common electricity, with differences that must naturally follow from the difference which exists between the motions of the fluid in the apparatus employed in the one case and the other.

497. Let us résume the experiment in which the pile communicates with the common ground. If we touch the summit of this pile with one hand and its

---

* Optice Lucis, edit. Lausannæ et Genevæ, lib. iii. quæst. xxxi, p. 304.

base with the other, we shall experience a continuous commotion that sets on edge the organs, if we may so speak, and is sometimes felt only in the hand, and at others extends to the elbow, according to the tension of the pile. In this case the pile discharges at its summit the excess of fluid of its different discs, at the same time that it repairs the loss, by means of the fluid which it regains at its base; and there is thus an uninterrupted electrical current, shared between the organs and the reservoir, and it is this which occasions in the former the sensation we have described.

498. Let us now suppose the pile insulated. Its lower half being then in a negative state, or in a state of resinous electricity, will instantly tend to regain from the organs the quantity of vitreous fluid necessary to restore it to the same state as when it was not insulated, that is, to the state in which it was only charged with the quantities of vitreous fluid that augmented continually from the base to the summit. The circulation will then establish itself through the organs, as in the case of a non-insulated pile. But the organs being imperfect conductors, it happens that when the pile is insulated, the column recharges itself in general less rapidly than when it repairs its loss at the expense of the ground with which it is in communication, and on this account the effect of the commotion must be less sensible. But it appears that this diminution is more than compensated by the greater rapidity of the fluid in the first instance, and the more concentrated action of the discharge, of which the effect is no longer shared between the organs and the ground. This explanation accords with the experiments of the celebrated Van Marum, who has generally obtained from an insulated column more sensible effects than from a column not insulated, and has remarked, that

in the first instance the commotions in particular were very strong *.

499. If the precaution be taken of dipping the hands in water previous to touching the pile at its upper and lower extremity, the commotion will become much more sensible. In this case the liquid, of which the conductive faculty is greater than that of the organs, favours the transmission of the electricity through those organs. The commotion will be still further increased, if two metallic tubes be used to touch the pile, the hands being wet as before. If a chain of persons be formed, and the individual at one end of the chain touches the upper part of the pile, and the individual at the other end the base of the pile, and all the hands of the party are wet, the commotion will become general, provided the persons forming the chain do not exceed a certain number, which must be governed by the charge of the pile †.

500. We have hitherto supposed, that the humid bodies employed in the pile, were wetted with pure water. But if a saline solution, made, for example, with muriate of soda, or, which is better still, muriate of ammonia, be used, the commotion will be incomparably stronger. Volta has inferred from this circumstance, that the action of the pile was favoured by the saline solutions, principally from their augmenting the conductive faculty of the water with which the pieces of pasteboard or cloth were wetted.

These effects will take place in the same manner in the experiment with the glasses, where, for the commotion to be felt, it is simply necessary to place one hand in the water contained in the glass forming one

---

* Annales de Chimie, 30 Frimaire, year 10, p. 305, 306.

† Histoire du Galvanism, vol. II. p. 8.

extremity of the series, and the other hand in that of the glass situated at the opposite extremity.

If the hook of a Leyden phial be placed in contact with the top of the pile, while its exterior surface communicates with the surrounding bodies, the phial will be so strongly charged, that its tension will be nearly equal to that of the pile.

501. Suppose a loose piece of wire to be so fastened to the summit, and another to the base of the pile, that the two wires may incline towards each other with a little interval between their projecting extremities. If the wires have sufficient freedom of motion, their contrary electricities will determine them to approach each other till they meet, and if one of the wires be then taken from its position, the other will follow it, by continuing to adhere.

It is hence apparent, that between the effects resulting from common machines, and those produced by the pile, there is this difference, that in the former the effects are annihilated at the instant of contact, while in the other they remain as long as the contact is continued. The pile once charged, becomes thus a reservoir of electricity, which, without the aid, and as

503. This naturally leads us to a comparison of the effects of different piles, which are supposed to vary according to the number and size of their discs. We shall adopt here the results obtained by Van Marum, from a series of experiments executed with a discrimination and accuracy for which he is celebrated *. We have seen (487) that in proportion as the number of discs forming a column is increased, the column acts, other circumstances being equal, with the greater energy, from possessing a higher degree of tension. But suppose two columns formed of an equal number of discs, but whose diameters differ perceptibly from one another: on subjecting these columns to the same experiments, what will be the result? According to the observations of Van Marum, the tension will be the same in both; there will be no perceptible difference in the force of the commotions; but the column with the larger discs will possess a much greater power of melting wire.

504. The equality of tension in the two cases is by no means difficult to conceive. We may consider here a pile of large discs, as an assemblage of piles of small discs, placed one by the side of the other, and of which each would have a tension equal to that of a single pile separated: the only consequence would be, that the total quantity of fluid would be greater in the pile of large discs, than in the other pile; but the tension, which depends on the density (391), or the quantity of fluid accumulated in each point, will be the same on both sides.

505. To understand how it is, that in the commotions produced by the two piles there is no perceptible difference, we must reflect, that the commotion is not here, as in the Leyden experiment, an instantaneous

---

* Annales de Chimie, 30 Frimaire, year 10, p. 289, &c.

effect, it is the result of a multitude of little shocks, succeeding one another with inconceivable rapidity indeed, but still it is succession. We must further reflect, that the re-establishment of the different discs in their primitive state, in proportion as we discharge the pile, also takes place only by degrees; and it is for this reason, that when metallic conductors of considerable size are used, the pile requires a certain portion of time to regain the same degree of tension. Now, on the one hand, the initial effect, which takes place at the commencement of the discharge, is greater with the pile of large discs, in which there is a more considerable mass of fluid; but, on the other hand, in the succeeding moments, the return to the primitive state is not effected so rapidly in this pile, as in the pile with discs of smaller diameter, because the fluid requires more time to diffuse itself over wider surfaces, and obtain the same density. It appears then that a sort of compensation is established between the effect of the greater mass acting in the first instant of time, and that of the less velocity taking place in the succeeding instants, in such manner that the total effect does not sensibly exceed that which is produced by a pile with small discs, in which, in general, the velocity of the fluid is accelerated, but its mass is in other respects less considerable.

506. Let us now advert to the circumstance of the greater facility of the combustion, when a pile with large discs is used. And here the fluid acts in like manner with much superior efficacy by its mass in the first instant of time; which gives it the more advantage in determining the commencement of the combustion, as the wire may be compared to a slender canal, placed conveniently to receive an abundant and rapid discharge. The combustion however having once begun, is continued by the heat of the wire combined

with the action of the new quantities of fluid which follow in succession.

507. Van Marum directed his experiments to a comparison, not less interesting, between the charge of the pile and that of a battery of 25 glasses, the latter apparatus forming together a surface of 137½ square feet. He observed at first that a pile consisting of 220 pairs of metallic plates of silver and zinc, by means of a single contact as short as possible, charged the battery to a tension equal to what it possessed itself; so that the pile and the battery had the same effect on the electrometer. The commotions however produced by the battery were not so strong as those which were felt on using the pile: the reason of which is, that the discharge of the battery was limited to the action of the fluid it possessed at the instant of the commotion; whereas during the same instant, necessarily divisible however short it might be, the pile had already begun to recharge itself.

The effects of the pile were afterwards compared with those of an electrical machine having a plate 31 inches in diameter. The object was to ascertain how many contacts of the conductor of the machine would be necessary to charge a battery to the same degree of tension that would be effected by a single contact of the pile. That the results might be fairly compared, it was necessary to contrive that the battery, while in contact with the conductor, should not receive a greater portion of electricity than the conductor would furnish by a single movement of the plate of the same duration as the period of contact. To accomplish this, Van Marum applied a finger to the conductor while the plate was at work, and then took it away for an instant scarcely perceptible, but precisely equal to that of his placing in contact with the conductor a wire, which he presented with the other hand by means of an insulated body and that communicated with the ground of the battery. The charge of the battery was thus reduced to the fluid which the plate developed during the moment of contact; and the experiment shewed, that six of these contacts were necessary to charge the battery to the same degree of tension which followed from a single contact of the column *.

It is not possible to read these results without being astonished at the immense quantity of electric fluid that accumulates, in a very short space of time, in the Voltaic pile, and at the extreme quickness with which the same fluid is moved in that instrument; which had already excited no small degree of surprise from this circumstance, that it acquires its power of itself, without standing in need of extraneous aid.

Different Substances that may be used in forming the Pile.

508. We have hitherto considered the pile as composed of the three substances that are most commonly employed in its formation. But the attempts that have been made to vary the combination of its elements, have led to very interesting results relative to the influence which the different bodies that may be employed exercise on one another.

509. Any two metals, brought into contact, will be formed, as we have before observed (479), into two different and contrary states of electricity. But Volta has discovered, that these differences, compared together in a number of varying metals, exhibit a very

---

* Annales de Chimie, Frimaire, year 10, p. 297, et seq.

singular gradation. If, for instance, the following scale, silver, copper, iron, pewter, lead, zinc, be formed, the state of any one of these metals will differ so much more from the metal preceding, and supposed to be in contact with it, and so much less from the metal next in order: and the law by which this gradation takes place is such, that the difference between the first and last metal is equal to the amount of all the differences, reckoning from metal to metal in the series [*].

The better to fix our ideas, let us represent the difference between the silver and copper, supposed to be in contact, by 1; that between the copper and iron by 2; that between the iron and pewter by 3; that between the pewter and lead by 1; and that between the lead and zinc by 5. If we suppose a small pile formed of these six metals thus arranged, and the pile be in communication with the common reservoir, the state of the silver being zero, that of the copper will be 1, the iron 3, the pewter 6, the lead 7, and the zinc 12. The difference between the two extremes, silver and zinc, will accordingly be 12 *minus* zero, or simply 12, a sum equal to the amount of the differences 1, 2, 3, 4, 5, between the different metals in the order in which they stand.

Hence it follows, that a pile, of whatever height, the elements of which should exhibit the preceding series of metals, would produce no greater effect, than if it were composed of the two extreme metals only, distributed in pairs. But the result, which has led Volta to this inference, is worthy of being verified by accurate experiments.

510. We have supposed, that the bodies moistened by water which form a part in the construction of the

---

[*] Annales de Chimie, Frimaire, year 10, p. 251.

pile, performed the office only of conductors. It is probable however that they have a degree of influence on the production of the electric fluid, though it appears to be very small compared with what the metals exercise on one another. Attempts have been made to diversify the construction of the pile, by varying the substances of which it may be composed. Volta has discovered, that instead of the usual metals, pyrite and charcoal might be used *. Gautherot has obtained perceptible effects by substituting the last-mentioned substance instead of copper, and has also constructed piles in which one of the agents has been charcoal and the other schistus known by the name of *carpenter's chalk* †. Mr. Davy has combined with success the action of charcoal, of nitrous acid, and of water, and M. Psaff that of a metal, with water and a sulphur, &c. ‡

From these and other observations of a similar nature, there appears to exist between the humid and the solid bodies a correlation that tends to vary, according to circumstances, the functions of those bodies; so that a humid substance, which, in one combination, performed the office of conductor, exer-

But Volta suspects, as we shall see presently, that an instance of the second kind is realised in the animal kingdom (*a*).

511. In the pile, as usually constructed, the metals undergo a ready oxydation, the inconvenience of which is not compensated by any perceptible influ-

---

(*a*) When M. Libes, the author of *Nouveau Dictionnaire de Physique*, had satisfied himself, that the contact of resinous with metallic substances developed electricity, he constructed a pile whose elements were, at first, 20 discs of resinous taffeta and of zinc, applied alternately one upon another, without any intermedium, commencing with the resin. The zinc disc which was towards the middle of the pile had a much greater diameter than the others. A glass cylinder was fixed at its centre, in such manner that it was easy to take off the upper half of the pile. The apparatus remained in that state for some minutes, after which he took the disc that occupied the middle by its glass handle, and presented to the electrometer the upper extremity of the pile, which was zinc; it yielded very perceptible signs of negative electricity: the other extremity of the pile which was resinous exhibited positive electricity. He did not experience any commotion, when, by means of his hands, he established a communication between the two extremities; whence he concluded that the pile had no electric foci.

In M. Libes's third attempt, the pile was composed of 40 discs of resinous taffeta, 40 of silver, 40 of zinc, 40 of paper which had imbibed a solution of muriat of ammoniac, ranged in this order: resinous taffeta, silver, zinc, and moistened paper. This pile possessed no electric foci: the silver and the zinc had the negative electricity; the resinous taffeta, the positive electricity: the oxydation was perceptible, but not very considerable.

Another kind of pile not mentioned by Haüy is the *Secondary Pile:* this name is given by *Ritter* to a pile which does not become electrified of itself, but receives the electric virtue when it is made to communicate with an electric pile. Ritter has given different modifications to these piles; having constructed several piles with a single metal, and others with various heterogeneous metals. When treating of these, he exhibits different methods of rendering piles inactive: as,

1. *Electric piles rendered inactive by* adossement, *or placing back to back.* Take two electric piles which only differ in the position of their poles; the inferior disc of one being zinc, and its superior disc copper; the other pile being the reverse of this. Place these two piles one upon another, so that they shall touch at their opposite poles, and thus constitute a pile whose number of discs is double that of each of its component piles: this large pile will become inactive, because the action of one half of it destroys that of the other half. If this pile be made to communicate with an electric pile in ac-

ence favouring the electrisation, as will appear hereafter; and further, the pieces of wet cloth interposed between the elements of the pile soon become dry, which deprives the apparatus of its efficacy. Of the attempts hitherto made to remedy these inconveniences, none have been better calculated to answer the purpose, than those of a young philosopher of the name of Alliseau, whose zealous research is entitled to commendation. He has constructed a pile in which

---

tivity, it will become charged, and excite strong commotions: but its chemical action is evanescent.

2. *An electric pile rendered inactive by the disposition of its elements.* Take a certain number of couples of copper and zinc, and dispose them in the following manner: If the first couple situated upon the base is copper and zinc, the second must be zinc and copper; the third, copper and zinc; the fourth, zinc and copper, and so throughout. The inversion made in the two halves of the preceding pile, is found in each couple of this; and it is obvious that this inversion destroys the activity of the pile; which will, notwithstanding, become charged when it is made to communicate with an active electric pile. The commotions which result from this disposition are weaker than in the former; and here also there is no perceptible chemical action. Hence Ritter infers, that the chemical action and the disturbing or electric action are separable, and that the one may exist independently of the other.

3. *A pile of two metals rendered inactive by their separation.* To form an

the elements are separated by porcelaine rings filled with crystals of marine salt wetted with water. Experiments having been made, to ascertain the difference between this and a common pile, it was found, that its effects, after a period of 53 days, were nearly the same as when it was first constructed, while those of the common pile lasted scarcely three days. The only precaution necessary was that of repairing from time to time the losses occasioned by evaporation. The pile having been taken to pieces after the 53 days, it appeared that the metallic discs were very little oxydated, which offers another advantage, beside that of permanence of effect, that may be extremely useful in certain experiments *.

Electric Fishes.

512. The quality possessed by a fish of the ray species, of benumbing the members of those who touch it, has long been known; and it is from this quality that the name of *torpedo* has been given to it. But, while the first enquirers were at a loss to what to ascribe the effect expressed by this word, the Arabs stumbled, as it were, on an appellation more striking as to its analogy and more appropriate: they call this fish *râad* or *raasch*, which, in the language of these people, signifies *lightning*.

513. The organ by means of which the torpedo exerts its benumbing faculty, consists of a number of aponeurotic tubes, chiefly hexagonal, though some of them are pentagonal, arranged parallel to each other

---

* Extracted from the Report made to the Mathematical and Physical Class of the National Institute by Charles Hallé, deputed to examine the pile in question.

round the bronchiæ, and reaching from the skin above to the skin below. All these tubes are accurately closed at each extremity by an aponeurotic membrane, which extends over the whole surface of the organ on each side. Besides this, each tube is decussated horizontally by aponeurotic laminæ placed one over another at short distances, so that the tube may be considered as a series of cells placed one upon another. These cells are filled with a substance, which, according to the experiments of Geoffroy, is composed of albumen and gelatine * (*b*). Finally, the whole of this apparatus is furnished with nerves remarkable for their bulk, which are inserted between

---

* See the minute description which this learned naturalist has given of the torpedo and other fishes endowed with the same quality, in the fifth number of Annales du Museum d'Histoire Nat. p. 392 et seq.

(*b*) In the 63d vol. of the Philosophical Transactions, Mr. Hunter also describes the electric organ of the torpedo as consisting of a number of columns varying in their length from an inch and a half to a quarter of an inch, with diameters about a fifth of an inch. The number of columns in each organ of the torpedo which he presented to the Royal Society was about 470; but in a very large torpedo which he dissected the number of columns in one organ was 1182. These columns were composed of films parallel to the base of each; and the distance between each partition of the columns the tubes, and are ultimately distributed in the interior of their cells.

514. Reaumur has observed, that when the torpedo was inclined to bring its organ into action, it first insensibly diminished the curve on its back till it became flat, and sometimes even concave, and then by a sudden motion raised it again to its former convexity *. If the fish were at such periods touched with a finger, a sensation resembling numbness was felt.

515. By some philosophers this phenomenon is ascribed to the emission of an infinite number of corpuscles continually proceeding from the animal, but of which the discharge is greater in some circumstances than in others, and which, in penetrating the members, benumb them, either by insinuating themselves in too great a number, or from the routes they have to pass being ill adapted to their formation. Others suppose the action of the torpedo to consist in a particular trembling which it communicates to the nerves, and that hence results a disagreeable sensation, that deadens the member in which it is produced.

516. Another opinion, no better founded than the preceding ones, but which it is of more importance to controvert, is that of Schilling, who imagined that he had discovered in the Surinam eel, which is known to possess the same quality as the torpedo, very sensible magnetic effects. According to this naturalist, the eel, being placed near a loadstone, was attracted by that body, and remained adhering to it: it was separated with difficulty, and when separated was languid, and might be touched with impunity. He states further, that the loadstone which was used on this occasion, appeared to be covered with particles of iron,

---

* Mém. de l'Acad. des Sciences: year 1714.

and that when the fish was afterwards placed in water in which were filings of this metal, it became lively and regained its wonted vigour *.

These assertions have been completely refuted by many philosophers of eminence, and particularly by Ingenhousz and Spallanzani, who, having carefully repeated the experiments mentioned by Schilling, could not perceive that the magnet produced the slightest effect on the eel †. Mr. Hahn, medical professor at Leyden, who has discussed in a very judicious manner the opinion of Schilling, observes, that the rivers in America in which the Surinam eel is found carry along in their current a magnetic sand; and he presumes, that grains of this sand adhering to the glutinous skin of the fish, which was probably covered with it when Schilling made his experiments, might be a principal cause of the illusion by which that naturalist was misled ‡.

517. Dr. Bancroft appears to be the first who suspected an analogy to exist between the phenomena of the torpedo and those produced by electricity. Mr. Walsh, desirous of ascertaining the truth of this conjecture, made a number of experiments, the end of

other extremity was plunged in a basin of water standing on another table, on which were four other similar basins. The other brass wire in its suspended state had one of its extremities in the last of the five basins of water. Five persons were ranged round the second table. The first plunged a finger of one hand into the basin in which was the wire communicating with the wet napkin, and a finger of the other hand into the next basin. The second plunged a finger of one hand into this same basin, and a finger of the other hand into the basin next in order; and so on through the series, till the five persons were in communication with one another. Mr. Walsh, having taken the second wire by the part not in the water, touched the back of the torpedo with the extremity of this same part, and the five persons instantly felt a commotion, which, from the account they gave, differed in no respect from what is felt in the Leyden experiment, except that the shock was weaker. Mr. Walsh, who was not included in the chain, but had merely held the exciter, received no impression. This experiment was repeated several times even by a company of eight persons, and every time with the same success. It was remarked, that every effort which the torpedo made to give the shock, was accompanied with a depression of its eyes, from which its attempts to produce the same effect even on unorganised bodies were discoverable.

The same quality has been found in many other fishes, of which the most celebrated are the *gymnotus* or *electrical eel of Surinam*, mentioned before (516), and the *silurus electricus:* from which it appears that the electrical property, which philosophers might have been tempted to consider as the index of a generic relation between animals partaking of it, is merely a specific quality, forming as it were distinguishing characteristics in families in other respects very strikingly different from each other. It happens here nearly as in the mineral kingdom, where the property of acquiring electricity by heat is dispersed, so to speak, through bodies of different natures.

In electric fishes different from the torpedo an analogous organ is found, which is an assemblage of cells composed of aponeurotic laminæ interwoven together, and likewise filled with albumen and gelatine. But the general form of this organ, as well as its position, vary in different species.

519. Walsh, in repeating the experiments of the torpedo on the gymnotus, in which the benumbing quality is much more energetic, obtained a result that completely confirmed him in the opinion, of electricity being here the real agent. He applied to a piece of glass a sheet of pewter in which he had left a small separation or slit. This sheet had its two edges in communication with the body through which the discharge from the fish was made. At the moment of that discharge he observed the appearance of a spark which went beyond the little interval made in the sheet. That this experiment may succeed, the fish

through the water fishes of a different species, on which, having stupefied them, they seize as their prey.

521. We shall conclude this article with some particulars relative to the theory, by means of which attempts have been made to connect the phenomena in question with those of common electricity. Though Mr. Walsh tried in vain to obtain attractions and repulsions between balls of elder pith, suspended to threads connected with the torpedo, he yet regarded this fish as a kind of animated electrical instrument, and he endeavoured to explain the difference of the relations it bore in other respects to the Leyden phial. He observed, that the same quantity of electric fluid, which, compressed in this phial, was capable of producing effects well known to every philosopher, no longer acted in the same manner, if it were rarefied by being distributed over a number of large jars, of which the parts, coated with pewter sheeting, should give a total surface four hundred times greater than that of the furniture of the phial. For then there would no longer be perceptible attractions and repulsions; but the same fluid, so dilated, would still be capable of giving a shock at the moment of discharging the apparatus. Now this distribution took place in the torpedo, in which the electric fluid was diffused and rarefied over the sum of all the surfaces of the prisms forming the organ of that fish. This was all that theory at the time was capable of suggesting as the most plausible hypothesis; and it is remarkable, that philosophers did not hesitate to ascribe those phenomena to electricity, which are in reality the mere result of that same Galvanic action, which has since occasioned so many disputes among the learned of different countries, respecting the true nature of the fluid producing it,

The philosophers who succeeded Walsh continued to compare the commotions given by the torpedo to those occasioned by the Leyden phial. But since the discoveries of Volta, the pile ought to be the real instrument of comparison. This celebrated naturalist presumes, that among the humid substances of which the organ of the torpedo is composed, some are adapted to excite the electric virtue by their mutual contact, and others to transmit it: so that the superstructure of the different cells formed of those substances answers to that of the metals and humid conductors following each other in the pile *. The exact determination of these substances and their functions is a very interesting subject of enquiry; and the solution of the problem, reserved for the combined efforts of physics and zoology, will exhibit a new proof of the aid which the sciences may derive from one another, by proceeding in concert towards the same point.

Chemical Effects of Galvanic Electricity.

522. Two learned Englishmen, Carlisle and Nichol-

of these wires are placed in water so as to leave an interval between them. The oxygen appears in the form of bubbles at the extremity of the wire communicating with the zinc disc, which produces vitreous electricity, and the hydrogen disengages itself, in the same form, at the extremity of the wire in contact with the copper disc which forms the base of the pile, and gives resinous electricity. If the metals are oxydable, very few bubbles are seen at the extremity of the wire answering to the zinc disc, because the oxygen fixes itself to this wire, making it at the same time pass to a state of oxydation (*c*).

523. This new phenomenon soon attracted the attention of the learned, and particularly of chemists, whom it furnished with a problem requiring the most delicate management, to reconcile it with the theory relative to the nature of water. The first point they wished to ascertain was, if the oxygen and hydrogen preceeded from the same molecule of water, or from two distinct moleculæ. It had been remarked, that when the wires were plunged into two separate vessels, there was no disengagement of gas: but this might

---

(*c*) Mr. *Cruickshank* ascertained that when the wire coming from the zinc end of the pile is plunged into infusion of litmus, the infusion becomes red, and an acid, which appears to be the nitric, is formed; that the wire from the silver end reddens the infusion of brazil wood, and of course an alkali is formed. He ascertained also, that the silver-end wire revives metals from their salts, as had been previously known to happen whenever nascent hydrogen comes in contact with them. He thought, likewise, that he had ascertained that all liquids containing no oxygen are non-conductors of Galvanism.

To avoid the trouble of re-piling the pieces of silver and zinc, Mr. Cruickshank constructed a kind of trough of baked wood in which he arranged them, which in many cases furnishes a convenient portable substitute for the pile. Mr. Pepys's Galvanic apparatus (mentioned in note (*e*), par. 510.) is an improvement upon this.—Tr.

arise from the communication, that was necessary for the discharge of the pile to take place, being then interrupted. Mr. Davy (*d*) devised a very simple mode of proving, that in reality it was this interruption which prevented the gas from disengaging itself. He plunged two fingers of the same hand into the two vessels, and the gas immediately appeared.

524. Several questions present themselves in this stage of our subject. Is it conceivable, that it can be the same molecule of water that is decomposed, when there is a very manifest interval between the two gases that disengage themselves? And if the decomposition takes place in regard to two different moleculæ, what becomes of the hydrogen in the part where oxygen only is perceived, and in its turn of the oxygen where the hydrogen alone is apparent?

The most natural solution of this difficulty that has yet been suggested, is that proposed by Monge and Bertholet *. According to these philosophers, the vitreous fluid has the property of disengaging the oxygen in preference to the hydrogen; and the resinous fluid the contrary quality. On the other hand, water, like every other compound substance, has the faculty of receiving different relative quantities of the elements that concur in its formation. Thus the water of dew is oxygenated, and it is from this circumstance that it contributes to the bleaching of thread or linen exposed to the air. Distilled water, on the contrary, is hydrogenated, which accounts for the savour it loses on being violently shaken in contact with air. We may suppose then, that, in the experiment we have cited, the water of each vessel, or that which is confined in each branch of the same tube, retains in excess that species of the two gases that does not exhibit itself.

525. The phenomenon of the decomposition of water by Galvanic electricity, furnishes a new object of comparison between the effects of the ordinary machine and those of the pile. Van Marum has obtained the same result, by passing a strong charge through an iron wire immerged in water *. Wollaston has repeated the experiment with a very fine gold wire, so fastened in a glass capillary tube, that its extremity, which was scarcely visible, should be on a level with the surface of the tube †. This celebrated chemist, by thus reducing to an extreme minuteness the quantity of metal subjected to the electric action, has succeeded in decomposing water, by a succession of little sparks issuing from a conductor charged in the common way. He has attempted also to excite, by similar experiments, the disengagement of the two component principles of water, by employing two wires immerged in this liquid at a distance. But he constantly observed, that each of the wires furnished

---

* Annales de Chimie, No. 121, p. 77.

† Biblioth. Britan. vol. XVIII. p. 33, et seq.

at once hydrogen and oxygen, while the action of the pile had the effect of exhibiting them separately (*e*). Hitherto, it must be confessed, experience has not spoken in terms sufficiently clear, to leave no desi-

---

(*e*) Dr. Wollaston's experiments and observations are published in the Philosophical Transactions for 1801: as they are not a little curious, it may not be amiss to give rather more minute information than M. Haüy could gather from the work he quotes.

This philosopher justly suspected with regard to the decomposition of water, that, by reducing the surface of communication, it might be effected by much less powerful means than had been commonly imagined: and this suspicion he verified. "Having," he says, "procured a small wire of fine gold, and given it as fine a point as I could, I inserted it into a capillary glass tube; and, after heating the tube so as to make it adhere to the point, and cover it in every part, I gradually ground it down, till, with a pocket-lens, I could discern that the point of the gold was exposed. The success of this method exceeding my expectations, I coated several wires in the same manner, and found that when sparks from the conductors were made to pass through water by means of a point so guarded, a spark passing to the distance of one-eighth of an inch, would decompose water when the point exposed did not exceed $\frac{1}{700}$ of an inch in diameter; with another point which I estimated at $\frac{1}{1500}$ of an inch, a succession of sparks, $\frac{1}{20}$ of an inch in length, afforded a current of small bubbles of air. I have since found, that the same apparatus will decompose water with a wire $\frac{1}{40}$ of an inch diameter, coated in the manner before described, if the spark from the prime conductor passes to the distance of $\frac{4}{10}$ of an inch of air."

derata, as to the theory of the phenomenon we are considering: new facts are wanted, that may serve as interpreters to the old.

526. Another chemical effect, which takes place spontaneously in every pile constructed in the ordinary way, is the oxydation of the metallic surfaces in contact with humid conductors. Some naturalists have thought, that this effect had a considerable influence in producing the electricity that developes itself in the pile. Biot, desirous of throwing some light on this interesting question, entered on a series of experiments, which he conducted with that accuracy and discriminating attention, that can alone lead to decisive results. The condenser he made use of, had its collecting plate fastened to a stem moveable from the bottom to the top, so that he could raise the plate to a level with the summit of the pile. On that summit he placed a small iron vessel filled with mercury. The extremity of the flexible stem of the condenser was also iron. This being raised to the height of the pile, the flexible stem was let down into the mercury by means of a varnished glass tube, and was then left to its own elasticity. In this manner the condenser continually received charges that were comparable. Its contact with the mercury, which transmitted to it the electricity of the pile, was always the same, and might have been continued or interrupted at pleasure. The quantities of fluid with which it charged itself were measured by an electrical scale constructed on Coulomb's plan (393).

A pile consisting only of twenty couples of metallic discs was employed; the humid conductors being round bits of cloth impregnated with a solution of sulphate of alumine. The pile being insulated on a cake of resin, the condenser, placed simply in communication with its summit, acquired no degree of electricity that was appreciable, on account of the little height that was given to the pile; but this circumstance was favourable to the success of the experiment, as it afforded an opportunity of better ascertaining the increase of electricity that would have arisen in the pile from the prolonged influence of the oxydation; and it followed at the same time, that the pile was well insulated. In another sense, the pile was in full energy, for if the condenser were applied to its summit for half a second only, and the base were touched at the same instant, a charge was obtained, that, measured by the scale, produced a repulsion of 90 degrees.

A communication was afterwards established between the top and bottom of the pile, by means of a wire, which, in contact at one of its extremities with the base, had the other extremity immerged in the vessel of mercury on the summit of the pile. The condenser, we are assured, did not then charge itself, whether the base of the pile were touched or not while the condenser was applied to its summit: which shews that the communication was well established.

It is known in this case, that the electrical current [illegible] ducting wire having been detached from the summit of the pile, by means of a varnished glass tube, and the condenser then applied to the same summit, there was no apparent electricity; yet the pile had still all its energy, for it was only necessary to touch its base during the application of the condenser, for the instrument to charge itself, as before, with a quantity of fluid of which the repulsive force was 90 degrees.

527. Let us attend to the inferences which Biot derives from these results. Suppose the oxydation had developed only a sufficient quantity of electricity to produce a repulsion of two degrees; that quantity could not have escaped observation. Now, from the calculations of our author, electrical intensities, measured by Coulomb's balance, are nearly proportional to the cubes of the angles of repulsion[*]. Accordingly, the quantity of electricity produced by oxydation during the space of two minutes, being necessarily less than two degrees, its relation with the total effect, observed before, was less than that of 1 to 90000; and as half a second only was requisite, in the first case, to charge the condenser, the share

---

[*] Let F be the repulsive force at a distance represented by unit. Let a be the arc of the circle described in consequence of a given repulsion. If this arc be so small as to be capable of being confounded with its chord, the repulsive force at the distance a will be $\frac{F}{a^2}$. Let T be the force of torsion at the distance 1; and it will be $T\,a$ at the distance a; and since there is an equilibrium between the two powers, we shall have $F = T \,.\, a^3$. In another experiment, if the distance be designated by a', and the corresponding repulsive force in the same scale be represented by F', we shall have $F' = T \,.\, a'^3$. Therefore $F : F' :: a^3 : a'^3$. By means of this result, we have the advantage of being able to compare with each other the repulsive forces that take place in a series of experiments, without being obliged to estimate the forces of torsion. The author has extended this result to electrical attractions, and has also determined the relation between two forces which come into equilibrium, in the case where the arc a is too large to be confounded, without manifest error, with its chord, which measures the real distance.

which the oxydation had in this instantaneous effect must have been below $\frac{1}{200000000}$; a quantity too diminutive to be appreciated. Thus, though in strictness the oxydation ought to develope electricity in the Voltaic pile, the effect of that cause is no way comparable with that which is produced by the contact of metals incessantly deriving aliment from contact with the earth.

528. Those philosophers who have ascribed so powerful an influence to so feeble a cause, have not sufficiently attended to the possibility of diminishing that influence, without altering the quantity of electric fluid developed by the apparatus. Biot has constructed piles in which, instead of humid substances, discs of nitrate of potash, carefully preserved from all humidity, were substituted. These piles give as much electricity as those in which the conductors are impregnated with very powerful saline solutions, for example, those which contain sulphate of alumine. The only difference is, that instead of half a second, the condenser requires half a minute to charge itself, when in communication with the summit of a pile composed of 20 discs. By varying the duration of contact, the author has found, that the process of the operation is governed by a law represented by a logarithmic curve.

527. If we now look back to the different results we have stated, we shall find in all of them a striking analogy between the agent producing them and the electric fluid. Let us revert first to the phenomena best calculated to exhibit this analogy. A Leyden phial, placed in contact with the pile, charges itself, and is capable of giving a shock, precisely as if it had been applied to the conductor of a common machine. The pile occasions attractions and repulsions similar to those of electrised bodies. The fluid which it fur-

nishes, accumulated in a condenser, emits sparks on the application of an exciter. Thus far the resemblance of effects indicates a similarity of causes. The sensation indeed which is felt on touching the pile at its two extremities, is not the same as that which is produced by the Leyden phial; but the reason is, that the first is modified by the progressive and continued action of the fluid, which, instead of striking the organs with a full charge at once, as in the Leyden experiment, attacks them by a rapid succession of little impulsions: and as a proof, that it is this fluid which animates the pile, transfer it into the phial, and the mere change of vehicle gives it all its qualities.

We have seen, that it was, in like manner, by no means difficult to explain other singularities of the pile, particularly the readiness with which a wire placed in contact with it enters into a state of combustion; while, judging from the extreme feebleness of its action on the electrometer, so powerful an effect was not to be expected from it.

The reciprocal influence which other solid bodies exercise on one another, even the nerves and muscles of an animal, is in reality of the same kind as that which takes place between metals; and it was useless to resort to a particular fluid by which to explain effects, that resemble in so many other respects those produced by metallic substances.

The parallel between the two electricities extends still further, even to the phenomenon of the decomposition of water; and if the circumstances accompanying it vary, accordingly as the pile or a common electrical machine is employed, the reason of this difference is manifest in the difference between the two apparatuses. Further researches may dissipate the cloud in which this branch of science is still enveloped; yet it will not be, by establishing an essential distinction between Galvanism and electricity, but by reconciling electricity with itself.

In fine, we may ask, whether the differences in the two cases, which have led to the supposition of different agents being concerned in producing the phenomena, are greater than those observable in the effects of common electricity alone? There, one body transmits the electric fluid rapidly to contiguous bodies, while another obstinately retains it in its pores. In some, it is communication, by means of contact, that excites the electric fluid; in others, friction; and in others again, heat. The slight sensation that is felt on drawing a spark from the conductor with a finger, and the shock which the Leyden phial gives, furnish also a more striking contrast, than what is occasioned by the discharge of the pile. The electric fluid indeed seems every-where to multiply itself by the diversity of its phenomena; and so accustomed have we been to its metamorphoses, that the new form it assumes in the nascent science of Galvanism might be deemed an additional reason for acknowledging it (*f*).

and armed with metal, we touch a jar discharged previously by dry hands, we feel the same sensation as from the pile.

Ritter reduces all the effect of the pile on the body to expansion and contraction; the positive conductor expanding, the negative contracting, the part. The pulse is made stronger by the positive conductor; weaker by the negative. The expansion is followed by a sense of heat, and *vice versa*.

The action of the pile on the organs of sense depends on the nature of the organ; but the two poles produce the extremes of the sensation. The eye in the positive state sees objects red, large, and distinct; in the negative, blue, small, and more obscure. On the tongue the positive pole produces an acid taste; the negative, an alkaline. In the nose, the negative produces an alkaline smell; the positive, that of oxygenated muriatic acid. The ears, touched by the positive conductor, hear a grave sound; and by the negative, a sound more acute.

Mr. *Creve*, a surgeon at Wurtzburg, had an opportunity of observing the Galvanic irritation on the leg of a boy, which had been amputated far above the knee in the hospital of that city. Immediately after the amputation, Mr. Creve laid bare the crural nerve *(kniekehlnerven)*, and surrounded it with a slip of tinfoil. He touched at once the tinfoil and the nerve with a French crown-piece. In that instant the most violent convulsions took place in the leg both above and below the knee. The remainder of the thigh-bone bent with force towards the calf; the foot was more bent than extended. All these motions were made with much force and rapidity. None were produced when the tinfoil was taken away, or when a steel pincer was used instead of a piece of silver, or when the tin or silver was covered with blood: but they were renewed when these obstacles were removed. These phenomena continued till 38 minutes after the amputation, when the limb became cold.

According to M. *Libes*, among the muscular organs of man and red-blooded animals, the heart retains the Galvanic excitability for the longest time. From the experiments of *Nysten*, the heart of a decapitated man was still sensible of the Galvanic action four hours and a half after his death, and that of a frog five hours after its death: whence that naturalist concluded that the heart, the organ which first gives signs of life, is also that which yields it last. This inference, however, is not acceded to by later enquirers.

M. *Aldini*, professor at the Institute of Bologna (mentioned in par. 466), has directed many of his interesting experiments to human subjects; and these he repeated at Paris, London, Oxford, &c. In the beginning of 1802, the professor had the courage to apply Galvanic electricity at Bologna to the bodies of various criminals who had suffered death at that place, and by means of the pile he excited the remaining vital forces in a most astonishing manner. This stimulus produced the most horrible contortions and grimaces by the motions of the muscles of the head and face; and an hour and a quarter after death, the arm of one of the decollated bodies was elevated eight inches from the table on which it was supported, and this even when a considerable weight was placed in the hand. These experiments have since been confirmed in various parts of Italy, particularly at Turin, by Professors Giulio, Vassali, and Rossi.

In January 1803, Professor Aldini repeated his experiments at the Anatomical Theatre, St. Thomas's Hospital. The following account of some of his experiments on a human subject is copied from the newspapers:

"The body of Forster, who was executed on Monday the 17th of January, 1803, for murder, was conveyed to a house not far distant, where it was subjected to the Galvanic process by Professor Aldini, under the inspection of Mr. Keate, Mr. Carpue, and several other professional gentlemen. M. Aldini shewed the eminent and superior powers of Galvanism to be far beyond any other stimulant in nature. On the first application of the process to the face, the jaw of the deceased criminal began to quiver, the adjoining muscles were horribly contorted, and one eye was actually opened. In the subsequent part of the process, the right hand was raised and clenched, and the legs and thighs were set in motion. It appeared to the uninformed part of the by-standers as if the wretched man was on the eve of being restored to life. This, however, was impossible, as several of his friends, who were under the scaffold, had violently pulled his legs, in order to put a more speedy termination to his sufferings. The experiment, in fact, was of a better use and tendency. Its object was to shew the excitability of the human frame, when this animal electricity is duly applied. In cases of drowning or suffocation, it promises to be of the utmost use, by reviving the action of the lungs, and thereby rekindling the expiring spark of vitality. In cases of apoplexy, or disorders of the head, it offers also most encouraging prospects for the benefit of mankind. The professor, we understand, has made use of Galvanism also in several cases of insanity, and with complete success. It is the opinion of the first medical men, that this discovery, if rightly managed and duly prosecuted, cannot fail to be of great, and perhaps, as yet, unforeseen utility."

5. Motion or raising up of the arm was produced (as if by volition) by the Galvanic stimulus.

6. A milky or coagulated matter was formed by repeated contractions of the muscle in contact with the copper wire, or wire of copper plated with silver: and the same appearance was seen when a plate of tinfoil was interposed, for then this white matter was formed on this tinfoil.

7. When the parts ceased to give out motion, or less motion, the motions were renewed with augmented force by wetting them with solution of sal-ammoniac.

8. It is scarcely necessary to remark, that the Galvanic stimulus excited contractions in parts which gave out no action to sulphuric acid, volatile alkali, and other stimuli.

Of the practical uses of Galvanism. The uses in common life of new facts are not always immediately apprehended; so that, although nothing very conclusive can be said, the present facts may be hereafter of great utility. In the meanwhile we observe:

1. That Galvanism may be a most powerful aid in restoring the vital actions suspended by submersion, by suspension, &c. although it does not act upon the lungs and heart; but if, at the same time that it excites the muscles in general, warm oxygen gas be applied to the lungs, and frictions and the hot-bath be employed, much more may be effected than without Galvanism.

2. In many diseases consisting in cessation of action, the parts may be excited to action by this new stimulus, *if it be duly applied.* For this purpose a machine is required which will of itself, without manual assistance, apply effectually the Galvanic fluid for any length of time. Such an instrument has been constructed by Mr. Cuthbertson.

3. In comparing electricity to Galvanism, it must be considered, that the former acts by its *intensity*, and the latter by its *quantity*: that the former, so intense, and sufficient if properly directed to knock a man down, shall yet not be in *quantity* enough to melt an iron wire or one of platina; but the latter shall melt these metals, yet scarcely produce a shock. See Phil. Mag. No. 56. Other interesting particulars relative to this branch of science may be found in different numbers of this Magazine, and of the Philosophical Journal; also in Wilkinson's History of Galvanism.—Tr.

VI. MAGNETISM.

530. The loadstone was long regarded as a simple stone possessing the property of attracting iron, as the name given, in the common language of every country, to the ferruginous mine endowed with this quality, will shew; such as *pierre d'aimant*, for example, in French, and the *loadstone* in English. Men judged of its substance by the stony particles that are often mixed with it, but which are purely accidental.

531. The attractive virtue of the loadstone was known to the ancients, and they had even remarked, that it communicated to one piece of iron the power of attracting another piece. But though, from the sympathy it seemed to evince for iron, the loadstone became one of those sports in which curiosity delights, and which it repaid in various ways, the best and most important property of this mineral, which occasions one of its extremities to have a northern and

the respective effluvia of two magnets met. There were supposed to be in the iron a kind of small hairs that performed the office of valves, to aid the passage of the fluid in one way, and to oppose its passage when it presented itself in a contrary direction. Such was, among others, the opinion of Dufay; and this philosopher, who had seen so clearly the principle of electric motion, when he came to apply it to magnetism, presented a machine of his own invention, instead of the mechanism of nature.

533. Æpinus was the first, who, to explain the phenomena of magnetism, made use of simple powers subjected to calculation. The idea which served as the basis of his theory was suggested to him while holding a tourmalin in his hand. He had discovered, that the effects of this stone were the result of electricity, and had remarked, that it repelled on one side, and attracted on the other, a small electrised body. To these two sides he gave the name of *poles*, and this appellation, which might have passed for a convenient mode of expression only, became the word really expressive of the thing. He saw in the tourmalin a kind of small electric magnet, and comparing the phenomena of real magnets with those of idio-electric bodies, he found, that the action of the two fluids might be reduced to the same laws; and thus added to the merit of having improved the theory of electricity, and created, as it were, the theory of magnetism, that of combining in the same link these two grand portions of the chain of human science.

Coulomb, receiving from the hands of Æpinus the first of these theories to give it a new modification, thereby contracted a sort of engagement to improve the second also; and it will presently be seen, from the sketch we shall give of his results, with what fidelity he has acquitted himself.

General Principles of the Theory of Magnetism.

534. Though the magnetic fluid is governed by the same laws as the electric fluid, there are several things, in the present state of our knowledge, that indicate a difference between them. Iron and one or two other metallic substances, are the only bodies that have hitherto exhibited unequivocal signs of magnetism, whereas all bodies are susceptible of the electric virtue. If an electrised tourmalin be presented to a magnetised needle freely suspended, whatever may be the direction of the two bodies as to the poles, the tourmalin exercises on the needle, to alter its position, the same attractive force only that it would exercise on any other body; which implies, that its presence gives rise in the needle itself to an electric virtue independent of the magnetic virtue.

535. The correspondence between the two theories leads us further to consider the magnetic fluid as composed of two distinct fluids, combined together in iron that exhibits no sign of magnetism, and existing apart in that which has undergone a state of magnet- [redacted]

But, before we proceed further, let us take a general view of magnetism as it presents itself in all its extent; for to understand well the developement of the theory, it is necessary to have at least an idea of it as a whole.

537. All the phenomena that magnets which have been subjected to experiment have furnished, are only so many different aspects, as it were, of a fundamental fact, that has long been remarked. It consists in this, that if we take at pleasure one of the extremities of a magnet, and apply it to the two extremities of another magnet, there will be attraction on one part and repulsion on the other between the two magnets. The opposed extremity of the first magnet will produce on those of the other magnet inverse effects. In general there is in every magnet two opposite points, that exhibit contrary actions, and to which the name of *poles* has been given. We may judge of the energy of these contrary influences, by making a magnet act in presence of a magnetised needle freely suspended; the extremities of this needle will make different circuits, and sometimes a complete revolution, to find the position required by the equilibrium.

538. Now we have a phenomenon, extremely remarkable by its continuity and the immense distances to which it extends itself, in the terrestrial globe, which performs, relatively to a magnetised needle, the same function as the magnet in the instance we have just mentioned: so that the needle, left to the influence of this vast magnetic body, takes a direction from north to south, and which we see to be that which accords with the manner of acting of this same governing influence. For if, when the needle is at rest, we alter its position, it never fails, after a few oscillations, to return to it again. What would have been the sentiments of the ancient philosophers, who

already ascribed a soul to magnets, though they knew nothing of their powers of action but in circumstances of contact, had the idea occurred to them of suspending one of these bodies to a thread?

539. What we have remarked in the preceding paragraph, leads to an observation that we conceive to be interesting, relative to the manner of denominating the two fluids which compose the magnetic fluid, as well as the poles in which their powers of action reside. The mere mention of the hypothesis relative to the existence of these fluids is sufficient to enable us to understand that the magnetic repulsions, similar in this respect to electric repulsions, are ascribable to those which exist between homogeneous fluids, and the attractions to those which heterogeneous fluids exert on one another. It follows from this, that when a magnetised needle is in its natural direction, the pole of that needle, which is turned to the north, is in the opposite state to that of the pole of our globe, which is in the same quarter; and as this last-mentioned pole ought to be the true north pole relative to magnetism, as it is with respect to the four cardinal points, it would seem more appropriate to give the

which is constant; so that it can derive no additional portion from any extraneous body, nor communicate the smallest portion of what it possesses by nature; and the change to a state of magnetism depends solely on the disengagement of the two fluids which constitute the natural fluid, and their passage to opposite parts of the iron.

541. The harder this métal is, the greater is the difficulty which the two fluids experience in moving in its pores; and, generally speaking, this difficulty is always considerable, and much superior to the resistance which bodies even the most perfectly idio-electric oppose to the internal motion of fluids disengaged from their natural fluid. Coulomb has given to this power the name of *coercive force,* as he has to that which acts in idio-electric bodies.

542. The property which magnetic needles possess, of turning one of their extremities to the north and the other to the south, depends on the circumstance, as we have stated (538), of the terrestrial globe performing with regard to those needles the function of a real magnet. In the developement of the effects which magnetic bodies subjected to experiment exhibit, attention to this action of the globe on magnetic needles is often extremely necessary. But as the science is yet too little advanced, relatively to this point, for us, by the aid of theory, to ascertain directly and with the proper precision the influence of that action, the defect has been supplied by the results of observation, which have been assumed as principles, from want of those which a more profound knowledge of the cause of natural magnetism would furnish. Among these results there are two which are particularly remarkable, and which we proceed to state.

543. When a magnetic needle is suspended freely to a thread, its austral pole is drawn towards the north,

while its boreal pole is attracted in a contrary direction, to the south; and it is evident, that in the case where the two forces which acted on this needle might vary in their intenseness, their resulting force acting always in a single right line, the needle constantly remained in that same line. But observation further proves, that the two actions which attract the needle in two contrary directions are apparently equal, in whatever point of the globe the needle may be. This is the necessary consequence of an experiment by Bouguer, who, having suspended by the middle, to a thread, a needle not magnetised, in which case the thread was vertical, and having afterwards magnetised the needle, observed that the thread remained in the same perpendicular position. Coulomb has obtained the same inference from the weight of a magnetised needle continuing precisely as it was previously to the magnetic virtue having been communicated to it. We see in effect, that if one of the two actions were superior to the other, its excess might be considered as a distinct force, the direction of which forming an angle with that of gravitation would give a compound motion, so that the needle would no longer exert the single force perpendicular to the needle, and applied to a point between the middle of the needle and the extremity answering to the nearest pole. This force is called *the directing force of the needle*, and observation shews that it is proportional to the sine of the angle which the needle, moved out of its natural direction, makes with that direction itself.

Coulomb has obtained this result by means of an experiment similar to the one he employed to ascertain the electric force placed in equilibrium with the force of torsion of a very thin metallic wire (392). We may recollect here, that the force of torsion, other circumstances being equal, is proportional to the angle of torsion, or to the number of degrees which any point, taken on the surface of the wire, passes over while the torsion is going on. This principle being laid down, and the needle suspended freely to a wire exempt from all torsion, Coulomb impresses upon this wire a torsion of a certain number of degrees; and the needle then departs from its magnetic meridian, till the directing force which tends to restore it to that meridian is in equilibrium with the force of torsion. The observer measures the angle which the needle then makes with its first direction, and gives to the wire a further torsion of a certain number of degrees. In this case the needle departs still more from its magnetic meridian, and at the same time the directing force that tends to restore it to that position, becomes augmented, because the forces of which it is the result act in less oblique directions along the needle. The torsion being at an end, the needle assumes anew the position under which the directing force is still in equilibrium with the force of torsion, which is measured by the first torsion, *plus* the augmentation it has received. Now it is ascertained that the number of degrees which the two torsions measure, are proportional to the angles which the needle makes with its original direction, in the two positions which furnished the equilibrium.

545. This result leads to another, which is merely a corollary from it. Whatever may be the direction of the real forces that act on the different points of the needle to restore it to its magnetic meridian when it has been made to depart from it, we may always ascribe to those forces a resultant parallel to the magnetic meridian; and it is easy to conceive, that this resultant must pass by a point in that half of the needle which answers to the north pole of the globe, if the experiment be made in a northern country, or, in a contrary case, to the south pole. Now, assuming as a fact that the directing forces are in proportion to the sines of the angles of deviation, it appears that the resulting force we have mentioned is a constant quantity, passing always by one and the same point of the needle.

The accuracy of this inference may easily be shewn. Let us suppose that, $n\,c\,k$ (fig. 58, pl. IX.) being the direction of the needle in its magnetic meridian, this needle be made to assume the direction $l\,c\,f$; the directing force may be considered as a power applied to the extremity f of the lever $c\,f$. Let it be represented by the line $f\,z$ perpendicular to $c\,f$. If, from the point f, we draw $f\,d$ parallel to $n\,k$, the resultant of all the forces acting on the needle, estimated parallel to the magnetic meridian, will coincide with $f\,d$. From the point z draw the line $z\,d$ parallel to $f\,c$, till it meets $f\,d$, and from the point f the sine $f\,g$ of the angle $f\,c\,k$; the triangle $d\,z\,f$ being similar to the triangle $c\,g\,f$, we shall have $f\,g : f\,z :: c\,f : d\,f$, or $\frac{fg}{fz}=\frac{cf}{df}$. But the first ratio is constant, because the directing force is proportional to the sine of the angle *f c k*. Therefore the second is constant also; and since *c f* is the radius, the resulting force *a f* will in like manner be a constant quantity, that will always pass through the point *f* of the needle.

But it was not sufficient to have established, by means of the results we have stated, a theory of magnetic phenomena: it was necessary to determine the law by which the forces that act in these phenomena are governed at different distances. Many philosophers, who devoted their attention to this subject, had recourse to means so very imperfect, that we must not be surprised to see their results accord so little with one another, and be so remote from the true principle*.

346. The precision of the methods employed by Coulomb, to ascertain this law, leaves no doubt that it follows the inverse ratio of the square of the distance, like that which governs electrical actions (392). But here, the manner in which the fluid is distributed in the bodies that were subjected to experiment, required distinct consideration; from the circumstance of these bodies having two centres of action that are in two opposite states, while the electrical bodies that were employed in researches directed to a similar end, were solicited only by a single electricity, which enabled the observer to consider all the forces as united in a single centre of action (53). For the present we shall content ourselves with remarking, that in the magnet the two centres of action are at a very trifling distance from the extremities.

Coulomb has obtained the end he had in view by two different methods. The first consisted in placing in a state of oscillation a small needle, 27 millimetres, or an inch, in length, directly opposite to the inferior centre of action of a magnetic steel wire, about 6·8 decimetres, or 25 inches, in length, situated vertically in the plane of the magnetic meridian.

---

* See the Physico-Mechanical Experiments of Hauksbee.

Leaving for an instant the superior centre of action out of the question, we must conceive that the needle, while it makes its oscillations, is at the same time solicited by two forces, of which one resides in the inferior centre of action of the steel wire, and the other is the directing force of the needle. The effect of this last force also, when it acts alone on a needle in a deranged state as to its magnetic meridian, is to give to the needle an oscillatory motion. Now Coulomb had ascertained, prior to the experiment, that the needle, left to its own directing force, made 15 oscillations in 60 seconds. But it is with the needle here, as with the pendulum oscillating by virtue of its weight: and it is proved that the action of this force, to make the pendulum oscillate, is proportional to the square of the number of oscillations made in a given time, assumed for the unit of time. Accordingly, in the present hypothesis, which supposes the needle to be solicited at once by its own directing force and by that of the steel wire, the value of the last is obtained those at which the two actions exerted themselves; and it was relatively to this point, that the question of estimating the force of the wire in presence of which the needle oscillates, was undertaken.

An example will serve to throw light on all that has been said. The needle, being so placed that its centre of action was at the distance of 108 millimetres, or 4 inches, from the steel wire, made 41 oscillations in a minute: placed afterwards at double that distance, it made but 24 oscillations in a minute. The total forces then, which solicited the needle in its two positions, were respectively as the square of 41 is to that of 24, or as 1681 to 576. If from each of these numbers we take the square of 15, or 225, we shall have for the ratio between the forces of the steel wire, that of 1456 to 351, which differs but little from the proportion of 4 to 1 *. And as the corresponding distances are to each other as 1 is to 2, we may infer, that the forces are in the inverse ratio of the square of the distances.

The number of oscillations that took place in 60 seconds, did not however always give exactly the quantity of action exerted by the steel wire. That exactness only obtained, as to sense, so long as the needle was at distances from the steel wire small enough to permit the neglecting the force of the superior pole of that wire, which was then directed according to a line deviating but little from the vertical, and which, besides, acted much farther off than the

---

* The difference, 13, between 351 and the fourth part of 1456, which is 364, is but slightly perceptible, from its falling on the squares of the numbers giving the oscillations made by the needle; so that the difference corresponding to it, relatively to those last numbers, is but a fraction of unit. For example, if we suppose the needle in its second position to have made 24 oscillations plus $\frac{1}{4}$, we shall have, instead of 351, the number 363 plus a fraction, a result approaching very closely to 364.

inferior pole. But when the needle was placed at a greater distance from the steel wire, then the part of the decomposition or resolution of that force which was in the horizontal direction, as well as that according to which the inferior pole acted, would become more appreciable with respect to the force of that same pole, and hence it was only by making the little requisite correction, that one could be able to represent the law sought, with the suitable precision.

547. The other method was analogous to that which Coulomb had employed in electricity. He converted the electrical balance into a magnetic balance, supplying, by means of a long magnetic needle, the lever suspended to the wire, and substituting for the copper ball a similar needle placed vertically on the magnetic meridian. Such was the respective disposition of the two needles, that when that which was moveable was on the point of touching the other, by preserving its nearly horizontal position, the contact took place at one of the centres of action of the first, and the inferior centre of the second.

The natural tendency of the needle to return to its magnetic meridian, was here also a particular action from each impressed torsion the number of degrees which the distance of the needle from the meridian gave—that is to say, the quantity by which the torsion of the wire was counteracted, by virtue of the movement of the needle—he found that the force of the needle, to react against each torsion, amounted to as many times 35 degrees, as there were degrees in the arch measuring the distance of the needle from the meridian.

Having stated this, to render the method of Coulomb more clear, we shall give here a further explanation of one of his experiments. Let S (fig. 59) be the position of the inferior pole of the fixed needle, which we suppose to be the south pole. This needle being situated vertically in the plane of its magnetic meridian, Coulomb places in contact with that pole, the pole of the same name, S, of the moveable needle *s n*, and in such manner that the wire has no torsion. The fixed needle instantly repels the moveable needle to a distance of 24 degrees, so that the last needle takes the position *s′ n′*.

Now the tendency to return to the meridian acts in a contrary way to the motion which the moveable needle has just made, and of consequence so far diminishes the true repulsion, or that which would have taken place if no such tendency had existed: that is to say, this tendency supplies the force of torsion, which it would be necessary to add to that of 24 degrees, to keep the needle at the same distance by virtue of the repulsion alone. But when the needle is 24 degrees from the meridian, the torsion which measures its tendency to return thither, is equal to 35 times 24 degrees, which makes 840 degrees. The repulsion then, which it was the business to estimate, is equivalent to a torsion of 840 degrees *plus* 24 degrees, or 864 degrees.

Things being in this state, Coulomb gives to the wire a new torsion equal to three circumferences of the circle, in a contrary way to the motion of 24 degrees already made by the needle suspended to the wire; that is, in the direction *b* S *d*; and that needle then approaches within 17 degrees of the fixed needle, taking the position *s*″ *n*″. Now three times 360 degrees make 1080 degrees; and since this torsion is only a continuation of that which existed before *, and which was reduced to 17 degrees, we shall have 1097 degrees for the torsion that measures the mutual repulsive force of the two needles, *minus* the tendency to return to the meridian. But this tendency is equivalent to a force of torsion of 17 times 35 degrees, or 595 degrees; therefore if we add 595 degrees to 1097 degrees, the amount 1692 degrees will give the torsion that constitutes the equilibrium to the repulsion it was required to estimate.

Hence it follows that the two repulsions are to one another as 864 to 1692, which exhibits a proportion of nearly 1 to 2. But the corresponding distances were 24 and 17, of which the squares differ but little from 2 to 1, which shews that the magnetic repulsions distances, and the same results have been obtained by substituting attraction for repulsion.

2. *Magnetic Attractions and Repulsions.*

548. Having proceeded thus far on our subject, we are now capable of explaining the phenomena produced by magnets in consequence of their mutual actions. This explanation will in reality be very little more than expressing in other words what we have said (410) of the effects exhibited by idio-electric bodies, of which one part is in a vitreous, and the other in a resinous state, and particularly the tourmalin. We may suppose, if we please, that the boreal fluid of a magnet performs the same function as the vitreous fluid of the tourmalin, and the austral as the resinous fluid. On this supposition the resemblance of the phenomena, in the two branches of science, is limited to those which the two bodies exhibit, having each its natural quantity of fluid only, which may indeed be decomposed, but can never be either increased or diminished. Of consequence there will be this distinguishing character between the two fluids, that the electric fluid passes freely from one body to another, and, in certain circumstances, exhibits itself to the eye by sparks and streams of light, while the magnetic fluid acts in silence, and becomes perceptible only by the movements it occasions in other bodies placed within its sphere of attraction or repulsion. But if this mode of acting does not furnish the hope of phenomena equally striking with those which electricity affords, the phenomena it does exhibit should on that account be the more closely studied by the naturalist; since the more a cause would affect to con-

ceal itself, the greater would be the sagacity of those who should succeed in penetrating the mystery.

549. When two pieces of iron, A and B, placed near each other, are in the natural state, their equilibrium, like that of bodies which evince no sign of electricity, depends upon four forces that mutually destroy one another. Confining ourselves to the existence of these forces in the body A: since all action is reciprocal, we must conceive the austral fluid of this body to act by attraction on the boreal fluid of B, and by repulsion on its austral fluid; and that, on the other hand, the boreal fluid of A acts by attraction on the austral fluid of B, and by repulsion on its boreal fluid. A mode of reasoning similar to what we have adopted (406) relative to electrical actions, will prove that the four forces in question are equal to one another; and as there are two attractions and two repulsions, it follows that all the forces are in equilibrium.

550. We have seen (411) that when two idio-electric bodies, having their parts in opposite states, are brought near each other, they attract by their differently electrised sides, and repel by the sides similarly electrised. In the same manner, if two magnets, M, N, (fig. 60), be so placed as to each other, that M turns its boreal pole, B, towards the austral pole, *a*, of the magnet N; the boreal fluid of B, for example, being at a shorter distance from the magnet N, than the austral fluid of A, we may consider the magnet M as being wholly in the boreal state, by virtue of a force, B′, equal to the difference between the forces of A and of B; and as the force B′ acts by attraction on the austral fluid of the pole *a* more than it does on the boreal fluid of *b*, which is farther from the magnet M, attraction will be the prevailing power; and if the two

magnets have freedom of motion they will approach till they meet, and will adhere to each other: on the other hand, if the pole *b* were turned towards the pole B, as represented in figure 61, from the same mode of reasoning, with a simple inversion of the terms, it is obvious there will be repulsion between the two magnets. This will be the case also if we suppose these magnets to turn towards each other their poles, A, *a*, solicited by the austral fluid. In general, two magnets attract each other by their poles of different names, and repel each other by their poles of the same name.

551. Let us conceive the body N (fig. 60) a bar of iron, that, while in the natural state, finds itself so placed within the sphere of action of the magnet M, that that magnet turns its boreal pole, B, towards it. The force B′ of that magnet, equal to the surplus force of B over A, will act so as to decompose the fluid of N; and it is manifest, that the effect of this action will be to attract towards *a* the austral fluid disengaged from the combination, and to repel towards *b* the boreal fluid: in other words, the bar N will acquire itself the magnetic virtue, so that the nearest poles will be those of different names, and the two magnets will attract each other. The result will be the same, if we suppose the bar of iron to be presented to the magnet M on the opposite side, so that the magnet might turn its austral pole, A, towards it. Hence we infer, that when a bar, or any piece of iron in its natural state, is presented to a magnet, the action of the magnet communicates a magnetism contrary to that of the pole to which the bar was nearest, so that, in this case, there is always attraction between the two bodies. The naturalist here also merely avails himself of the magnetic fluid to repeat an electrical experiment; as that, for instance, in which a body, being in a certain state of electricity, first makes an-

other body quit its natural state, and then attracts it to itself (407).

552. The bar which has received the magnetic virtue, acts in its turn on the magnet that has communicated it, by decomposing a new portion of the natural fluid of that magnet, of which one part is attracted towards the pole nearest to the bar, and the other to the opposite pole. The same thing happens, for a stronger reason, when the magnetism is communicated to a bar by the immediate contact of another bar already magnetised. And hence a sort of paradox extremely embarrassing to those who admit of the principle of vortices or of magnetic effluvia, which is, that a magnet should become stronger when it would appear to have ceded a portion of the fluid in which its strength consisted. Meanwhile, this increase of virtue acquired by the magnet is perceptible only inasmuch as the coercive force of the magnet is very inconsiderable.

553. Reaumur was the first who observed, with surprise, that a magnet, which had scarcely the necessary power to sustain a piece of iron of a given weight, raised it more easily when the iron was placed on an

experiment a more favourable light, the two bodies to be in contact at their poles, B, *a*. If we place behind the body N, at the point *b*, a third body, in the natural state, the action of N will convert that body, in its turn, into a magnet of which the austral pole will be contiguous to the pole *b*; and this series may be continued to any length. There is a curious mode of varying this experiment, by presenting one of the poles of a small magnetic bar to one of the extremities of a sewing needle, and then to take up the bar so that the needle may remain suspended to it: the extremity of this needle will serve as a bait to attract a second needle, which will continue in like manner to be suspended to the first, and thus needle may be appended to needle as long as the magnetic force is sufficient to overcome the weight which tends by its action to break the chain.

555. There is another result, which, elementary as it may be at present, to those who understand but little of the theory of the magnet, exhibits so convincing a proof of that theory, that, for this circumstance alone, it deserves to be cited. Take two magnetic bars of nearly equal force, and present to each of them in turn a key which it is capable of raising, which it will do whatever be the pole that is placed in contact with the key. Then place one of the bars on a table so that one of its extremities may extend sufficiently for the key to remain suspended to it. Then put the other bar upon that to which the key is pendent, making the poles of different names correspond on the same side; and the key instantly falls, because the action which the pole in contact with it exerts to attract to itself the heterogeneous fluid of the key is nearly destroyed by the repulsive action of the second bar. Hence we see, that to explain the fact this principle is necessary, that iron placed in contact with a

magnet becomes itself a magnet. We see, too, the ground of the surprise which this effect produces, when the mind is not sufficiently on its guard against the paradox that presents itself to the eye, which is, that a force is destroyed by the addition of another force, which, acting alone, produces in appearance an effect entirely similar.

556. The action of magnetism transmits itself freely through all bodies not susceptible of acquiring it. Place for instance a board, a pane of glass, a plate of copper, &c. between two magnets, and there will be no apparent alteration in their reciprocal actions. Charlatanism availed itself of this quality possessed by magnetic forces of not being impeded by any obstacle, to give to the most ordinary phenomena an air of magic, by means of machinery, that concealed from the spectator the real agent.

But here even experience, free from all idea of disguise, leads to results, formed apparently to disconcert the sagacity of the philosopher himself: but a theory is never better established than when its principles, which at first were supposed to be shaken by the difficulties arising from those very results, derive, on the contrary, new strength from the happy solutions they furnished of them. We have already had occasion to cite several such solutions, and what we are about to offer will exhibit other instances equally remarkable.

557. Place vertically, at the distance of a few centimetres from each other, two bars of magnetised iron, with their contrary poles turned to the same side; then cover the upper extremities with a thin board or piece of paper strewed with iron filings, and these filings will so arrange themselves as to form a multitude of curves of greater or less width, which all cross one another in points situated immediately above

the upper extremities of the two magnets. Figure 62 is a kind of representation of this assemblage of curves.

Philosophers have considered this phenomenon as an evident demonstration of the action of magnetic vortices. Other experiments furnish only matter of conjecture as to their existence; but here do we not see them actually exhibit themselves?

We shall analyse this phenomenon, that we may the better understand its true interpretation, agreeably to the principles of our theory. Let C G (fig. 63, pl. X.) be a magnet having its centre of boreal action in B, and its centre of austral action in A. Conceive a ferruginous needle, extremely short, to be suspended freely at a point, N, nearer to B than to A. This needle, which we have hitherto supposed to be in the natural state, will itself become a magnet; and as we may then consider the magnet C G as solicited by a single force, the needle, by virtue of a certain quantity, B′, of boreal fluid, will assume an oblique position to the magnet, so that *a* will be its austral pole, and *b* its boreal pole. In this state of things, suppose the centre, *c*, of the needle to be moved a little along the line *a d*, or the line of prolongation of the needle, so that its centre, for example, shall be in *g*. In consequence of this single movement, the extremity, *a*, of the needle will approach towards the point B: from which it follows that the needle will assume a new position less oblique than the preceding, and directed according to the line *e m*, which will make with the line *b d* an infinitely small angle. If we give to the centre, *c*, a further movement along the line *e m*, so that this centre shall be in *f*, the needle will take another direction, such as *f l*, making a very slight inclination with the preceding direction. If we continue to move the centre of the needle in the same manner, it is obvious that this centre will describe a curve $c\,g\,f\,n$, &c. the sides of which will coincide with the different directions of the needle.

In this curve there will be a point where the needle, which continually departs from the parallelism with C G, will take a direction, $n\,r$, perpendicular to that line. Beyond that point, the extremity of the needle still tending to approach nearer and nearer to the point B, the new sides, $r\,s$, of the curve will be inclined in a contrary way to the first sides, $c\,g$, $g\,f$, &c. and at last, when the extremity, a, of the needle shall be indefinitely near to the point B, the curve will pass through that point. Below, it will form sides, which will approach continually nearer to parallelism with C G; and when the centre of the needle shall be at p, situated directly under the centre O of the magnet C G, the direction, $x\,y$, of the needle will be parallel to C G, because of the equilibrium between the forces of the poles B and A. Beyond that term, the force of the pole A being the preponderating force, the curve will incline towards A, and at last will pass there, forming a new branch, $x\,z$ A M, of the curve, similar to the opposite one.

Let us now imagine the centres of a multitude of extremely short needles to be arranged on the circumference of this curve: these needles will shortly assume such positions, that each of them will direct itself according to the tangent at the point of the curve, which will be confounded with the centre of the needle; and as all the needles are directed towards each other by their poles of different names, they will adhere to one another, and will form a continued curve.

If particles of filings be substituted for these needles, and instead of supposing these particles freely suspended, we conceive them to be laid on a plane where they experience a degree of friction, the resistance produced by the friction will prevent them from gliding towards the points A, B, which act to attract them; at the same time this attractive force may be such, that the filings will take the direction which they would have had, if placed so as to have been moveable round their centres, especially if we second their tendency, by slightly shaking the plane that supports them, so that they will form on that plane by their junction the curved line we have mentioned. We may comprehend without difficulty, that if the plane is covered with particles of filings, the particles will take a direction to the sides of different curved lines adapted to the corresponding systems of individual action, and the curves will have two common intersections at the points A and B, which is conformable to observation.

558. We may explain with the same ease a little phenomenon bearing some affinity with the preceding one, and which is the more curious, as it would seem, by its singularity, to make experience contradict theory. It is this: Place on a piece of board, or a table, O R (fig. 64), a slender iron wire, two or three millimetres in length, and hold above the table, at the distance of a few centimetres, a magnetic bar, A B, in a vertical position, having its lower extremity, which may be either the boreal or the austral pole, sideways as to the wire. The wire instantly raises it at the extremity nearest the bar, taking an oblique position such as *b a*. Shake the table slightly so as to jolt the wire a little, and you will see it regularly approach towards the bar, till it places itself in a vertical situation immediately under the pole B.

Thus far there is nothing which the observer might not have foreseen. But place the bar underneath the table, as is represented in figure 65, and proceed with the experiment as before, and the wire *b a* will raise itself again, making an angle more or less acute with the surface of the table; but in proportion as we slightly shake the table, the needle will continually remove from the bar, approaching the point R, though it is evident that the bar exerts on it an attractive force.

To solve this paradox, let us take the case in which the bar was above the table. Let B (fig. 66) be the inferior centre of action of this bar. At the moment the wire rises, we may consider it as a small lever, *a b*, the fulcrum of which is at the point *b*, and the extremity *a* is solicited at once by the attraction of the pole B, and by the weight which acts to make it descend. Now this last force opposes itself in part to the effect of the attraction of the pole B, so that the angle *a b s*, formed by the direction of the wire with the plane O R, is less than the angle B *b s*, which would have been formed on the supposition of the wire directing itself according to the line *b* B, which passes through the pole of the bar.

Now let us suppose the wire *a b*, in consequence of some force, to be detached from the plane O R, so that its centre of gravity, *c*, shall be a little above its first position, for instance at the point *c'* in the vertical line *u c z*: if we suppose, for an instant, it has taken the position *a' b'*, parallel to *a b*, it will not preserve it; but its extremities, *b'*, *a'*, having both in that case freedom of motion, the wire will turn round the point *c*, and will tend to direct itself on a line passing through the pole B, which cannot take place without its extremity *b'* lowering itself towards the plane O R; and when it shall touch it, the wire having a direction such as *b'' a''*, of which the prolongation passes through the pole B, or nearly so, its extremity *b''* will be nearer the vertical line *s* B, than when it had the position *b a*. At the same time, the resistance of the plane O R offering a new fulcrum to the small lever which rests on it by its extremity *b''*, this extremity will remain fixed, while the opposite extremity *a''* will descend a little from the effect of gravity, so that the angle *a'' b'' s* will diminish by a small quantity, continuing however always larger than the first angle *a b s*.

During the descent of the point *a''*, the centre of gravity *c'* will quit the vertical line *u z*, and place itself in the point *x*, on an arch of which *b'' c'* will be the radius, and accordingly it will approach nearer to *s* B. If we shake the plane O R a second time, and imagine a new vertical line, passing through the point *x* and along which the centre of gravity of the wire moves, the same effect will be repeated; and this will be the case every time, so that the point *b''* will have a progressive motion towards the point *s*, and will at last coincide with it, by directing itself according to the vertical line *s* B.

The supposition we have made of a vertical line, of which the centre of gravity of the wire follows the direction, by raising itself above its preceding position, is not very remote from the truth; for the distances of the poles *a*, *b*, of the wire from the pole B of the magnet, differing but little from one another, on account of the shortness of the wire, the two actions of the pole B, of which one attracts the pole *a*, and the other repels the pole *b*, are nearly equal; and as the shaking of the plane is supposed to act in a direction diametrically opposite to that of the weight, it follows, that the centre of gravity of the wire remains, as to sense, in the same vertical line, both while the wire ascends and while it descends.

The experiment ought to exhibit effects the reverse of these, when the magnet is placed underneath the plane O R, as in figure 67, where we suppose the pole A, the nearest to the plane O R, was the austral pole, which is immaterial as to the result. In this hypothesis, the wire having taken of itself the direction *b a*, if we give a slight shaking to the plane O R, and *c′* be the new position of the centre of gravity of the wire, it is easy to perceive, that this wire, instead of remaining in a direction, *a′ b′*, parallel to *a b*, will lower itself by its extremity *b′*, in such manner that when it shall touch the plane O R, the direction of the wire will be in the line *a″ b″* A, which passes through the pole A of the magnet: whence it follows, that the extremity *b″* will be farther from the vertical line A *s*, than in its first position. But at the same moment the wire, supported at the point *b″* by the plane, will descend by its extremity *a″*, in consequence of the weight, and its centre of gravity will be transferred to the right of the vertical line *u z*; from which it is easy to conceive how the new shocks given to the plane O R will determine it to approach the point R, so that the attraction exerted on it by the magnet will appear to be changed into repulsion.

559. We shall state another very easy experiment, which furnishes a numerous assemblage of little phenomena, similar to the one we have just explained.

magnet. This distribution, which is analogous to that of the electric fluid round a conductor, or of the two electric fluids in a tourmalin, is in general so arranged, that the magnetic densities being very considerable near the extremities, decrease rapidly from thence, and become almost nugatory in a very manifest space situated towards the middle of the magnet. It follows, that the centres of action of these bodies are, as we have stated (546), at a short distance from their extremities. For example, in a steel wire 67·5 cent. or 25 inches long, this distance was but 22·5 mill. or ten lines. We may form a pretty accurate judgment of this proximity of the centres of action with regard to the extremities of a magnetic steel wire or bar, by holding such a bar in a vertical position opposite the freely suspended needle of a compass, and by raising and lowering it, so that the different points in its length may be successively presented to the needle: in this case we shall observe in the needle a manifest tendency to a certain point of the bar, which will be little remote from the extremity situated on the same side.

This distribution of the two fluids in a magnet depends on the principle that the forces of these fluids conform to the inverse ratio of the square of the distance. To judge from appearances, the action of each moiety of a magnet proceeds wholly from the presence of a single fluid in a state of freedom. But every thing induces us to admit the happy hypothesis of Coulomb, which we have mentioned before in speaking of electricity (458). It consists in regarding every molecule of iron as a small magnet, that has its boreal pole and its austral pole equal in force to each other. All the petty magnets of which a magnetic bar is the assemblage, are ranged in different files parallel to the axis of the bar, in such manner that the boreal pole of one is contiguous to the austral pole of the next, or reciprocally. We shall attempt to shew how this hypothesis furnishes an equivalent to what would take place if each moiety of the magnet were in a single state of magnetism.

561. Conceive, in the first place, an indefinitely thin needle, *m n* (fig. 68), composed of an infinite number of small partial needles, *c*, *d*, *e*, *f*, &c. and suppose this needle to have been put into a state of magnetism by the action of a magnet. In this case, all the contrary forces of the contiguous poles b, a'; b', a'', &c. * will be equal to one another, so that their actions will be reduced to zero. As to the forces of the two extreme poles, videlicet, that of the pole *a* of the needle *c*, and that of the pole *b* of the needle *r*, which alone are in action, on account of their distance, the quantities of fluid on which they depend residing only in two points, these forces are supposed to act on all the intermediate poles at infinite distances, and their action is of consequence inefficient to alter the state of the whole needle. Hence, if there existed a magnetic needle similar to this, its two centres of action would be in the extreme points, and all the space between would be supposed to be in the natural state.

But the hypothesis of a needle infinitely thin is merely ideal, and all magnets have necessarily a thickness more or less apparent. Yet we may discover, by a train of reasoning, what ought to be the result of the reciprocal influence of different needles resembling the needle *m n*, of which a magnet is supposed to be the assemblage, to place that magnet in the state in which the experiment presents it to us.

---

* The letter *b* indicates he re, as before, the boreal pole, and the letter *a* the austral pole.

Let us imagine that M N being the magnet in question, the distribution of the two fluids is at first the same in each of its component needles, as that which takes place in the needle *m n*; let us suppose, further, this needle to be placed in contact with the magnet M N, so as to become one with it, and let us examine the action which it ought to exert on the different points of the needle. If we divide in imagination the magnet M N into as many parts, C, D, E, F, &c., as there are constituent needles in the needle *m n*, we shall have a series of magnets in which the forces of the contiguous poles B, A′; B′, A″, &c. will mutually destroy one another; and thus M N, in the present supposition, will not be able to act on the needle *m n* but by means of forces which have their seat in the extreme poles; such are the pole A of the part C, and the pole B of the part R. Now, each of these forces is that of a fluid which extends over a surface equal to the base of the part C or R, composed of an infinitude of points; from which it follows, that it acts at finite distances on all the little needles, *c*, *d*, *e*, *f*, &c.

Now the fluid of the superior pole A attracts to itself the boreal fluid of the pole *b*, *b′*, *b″*, &c. of each of these needles, and repels the austral fluid of the pole *a*, *a′*, *a″*, &c. There will then be a certain number of heterogeneous moleculæ that will re-unite themselves in every needle, and compose anew a portion of the natural fluid. But the fluid of the pole A acts more forcibly on the needles near the extremity *m*, and more feebly on those which are at a certain distance from its extremity. The quantity of natural fluid composed anew will therefore decrease from one needle to the other; and by a necessary consequence, the portions of fluid which remain in a disengaged state, will, on the contrary, go on increasing from the extremity m. The same effects will take place in the contrary way, by virtue of the action of the inferior pole B on the needles r, o, h, &c.

It follows from what has been said, that if we represent by a, b, a', b', &c. the quantities of fluid which remain in a disengaged state in the needles of which these letters have served to designate the poles, and if we compare the two needles c, d, we shall have a' greater than b; in like manner by comparing e with d, we shall have a'' greater than b', &c.; from which we conclude, that the action $a'-b$ of the first two poles, as well as the action $a''-b'$ of the two next, is equivalent to that of a single austral pole animated by a force equal to the excess of a' above b, or of a'' above b'. By employing the same mode of reasoning with regard to all the following poles till we come to the middle of the needle m n, we shall infer that all this half is in the same case as if it were solicited by a series of decreasing quantities of austral fluid. With respect to the inferior half of the needle m n, the reverse will be the fact. The differences, $b'-a$, $b''-a'$, &c. between the quantities of fluid belonging to the constituent needles r, o, &c. will each represent a bo-

But as the forces of the magnet M N follow the inverse ratio of the square of the distance, they will act on the needles near the extremities with an intenseness incomparably greater than on those at a certain distance from these extremities; so that if the needle *m n* be rather long, the effect of these forces on the middle part of the needle will be almost nugatory. Accordingly the fluids will preserve in this part nearly their primitive state; and that state, as follows by consequence, will differ but little from the natural state.

What we have said of the indefinitely thin needle, *m n*, may be equally applied to all the needles of which a magnet, M N, having a manifest thickness, is the assemblage, and that by virtue of the reciprocal actions of those needles; so that at the very instant in which this needle has been drawn from the natural state, there is established in its interior a general distribution of the two fluids, similar to that which, to aid our conceptions, we have supposed relatively to a single needle.

562. It is now easy to solve the difficulty presented by a phenomenon, that has excited in no small degree the astonishment of naturalists, and of which Æpinus himself gives but a very unsatisfactory account. Cut a magnetic bar towards one of its extremities, so as to detach a portion of it, that may be ever so short, and

---

proceeding in the same manner as to the other extremity, the state of *r* be represented by —6+6, that of *o* by —12+12, that of *h* by —15+15, and that of *g* by —16+16; it is evident, that the quantities of austral fluid that will remain in activity in the upper half of the needle, will form this series: +12—6, +15—12, +16—15, +16—16, or more simply, 6, 3, 1, 0. In the same manner the quantities of austral fluid that will remain in activity in the lower half of the needle will exhibit this series: +6—12, +12—15, +15—16, +16—16, or —6, —3, —1, 0. Thus each half of the needle will be conceived to be solicited by a single force equal and contrary to that of the other half.

instantly that portion becomes itself a complete magnet, having also its two halves solicited by equal and contrary forces. How, by the ordinary theories, is it conceivable, that this segment, which was before completely in a unique state, like the part from which it was separated, should all at once, by a sort of creation, be furnished with a double magnetism?

To unriddle this seeming paradox, let us again have recourse to the supposition of the indefinitely thin needle, *m n*, which presents, as we have seen, a succession of opposite poles, equal in forces, and contiguous two and two, except the first and last, which are apart. If we were to break this needle, at any point whatever of its length, it is evident, that each part would have still at its extremities two poles animated by equal and contrary forces, of which the one, which was at first remote, had then all its energy, and the other, which was balanced by the force of the contiguous pole, would be placed in activity, on separating itself from that pole.

The same thing will have place, if we suppose a portion of the magnet M N has been detached from its length; with this difference, that the pole situated similar in form, and disposed symmetrically in the whole body, that each molecule must completely undergo the double action of electricity or of magnetism, to place its two halves in different states: and accordingly the distinction between these states, as to entire bodies, is only a consequence of what takes place relatively to each molecule. The effect of the whole assimilates itself to that of the component parts; and thus, on this hypothesis, which is extremely plausible, there is no longer any thing extraordinary in the phenomena produced by those bodies, which may be termed the *polypi of the mineral kingdom.*

3. *Communication of Magnetism.*

564. We have already spoken (551) of the action exerted by a magnet on a piece of iron which, being first in the natural state, was afterwards placed within the sphere of activity of that magnet; and we have seen that it acquired itself the magnetic virtue, so that its part turned towards the magnet was in an opposite state to that of the pole which had acted on it at a nearer distance. We have now to explain the different means which have been devised to carry to the highest possible pitch the magnetism acquired by communication. But we must first give an idea of a result that has sometimes taken place, in consequence of an irregular distribution of the two fluids put in motion in a body passing to the state of magnetism.

565. Suppose A B (fig. 69) to be a powerful magnet which acts on a bar of iron, *m n*, to communicate to it the magnetic virtue: the action of this magnet, which will depend on the excess B′ of the force of the boreal pole B over that of the austral pole A (551),

will attract the austral fluid *a* in the parts of the bar near *n*, and repel the boreal fluid *b* in the parts situated towards *m*. Now there are two circumstances that occasion in the motion of this last fluid some obstacle: first, the difficulty which its moleculæ experience in moving the iron, which proceeds from the coercive force (541), and next the repulsion exerted on these moleculæ by those of the fluid already accumulated towards the extremity *m*; a repulsion that augments continually, in proportion as the accumulation itself continues to augment. Accordingly there may be a term where the resistance arising from the concourse of the two causes may become superior to the repulsive power of the force B′, and the fluid will then, if we may so speak, be choked up in some point, *b*′, by yielding to that resistance, and may even so abound there, that its action shall produce in the neighbouring part *a*′ austral magnetism.

The bar of iron, *m n*, will therefore, in that case, have four poles in succession to one another, and possessing alternately austral magnetism and boreal magnetism. To these different poles succeeding one another in the same magnet, the name of *consequent* quire one or two poles more, and the needle will then have three or four consequent points. It may also produce another effect, connected with the preceding, and which occasions a simple reversion of the poles of the needle, so that the austral pole will take the place of the boreal, and reciprocally.

The circumstance which determines one of these effects to take place rather than the other, depends on the relation between the force of the bar and that of the needle. Suppose the needle *m n* (fig. 70) being moveable on its pivot, we present it by its boreal pole, *b*, to the boreal pole, B, of a bar, holding it at the same time with the hand, to prevent its turning by the effect of repulsion. It will happen, that the force B′ of the bar (551) drives back all the fluid *b* to a certain distance from the extremity *n*, and at the same time decomposes a new portion of fluid which is still in the natural state in the needle, and attracts towards *n* the austral fluid which forms a part of that natural fluid. The needle will then have three consequent points, as represented in figure 71; so that if we successively cause to pass, directly opposite to its different points, the austral pole of another needle, not strong enough to change the state of the first, the two extremities of that needle will be repelled, and there will be, between those extremities, a point, such as *b*, that will be attracted.

567. But if the bar A B (fig. 70) be sufficiently powerful to overcome in all the points of the needle, *m n* the resistance of the coercive force, it will be able to act so as to repel as far as *m* the boreal fluid of the needle, and attract as far as *n* its austral fluid; and in that case the poles of the needle will be reversed, without any intervening pole between the extremities *m*, *n*.

568. The analogy between magnets and bodies su-

sceptible of electrisation by heat, extends even to this kind of anomaly which the consequent points exhibit. We have seen a topaz which, after having been heated, had its two extremities in a resinous state, while the part between evinced signs of vitreous electricity *.

569. To render more intelligible what we have to add upon this subject, we shall resume here, with more detail, what has been said (541) of the difference which the greater or less degree of hardness of the iron occasions, in general, in the internal motion of the fluid. Steel does not accommodate itself to this motion without great difficulty; but the two component fluids having once overcome the obstacles which prevented them from distributing themselves in the two halves of a steel bar, the same difficulty which had retarded this distribution opposes itself to the effect of the attractive force, which tends to bring back the two fluids to one another, and by their combination restore the bar to its natural state. On the contrary, in soft iron, the disengagement of the two fluids is effected more easily and more abundantly; but the return to the state of combination takes place afterwards with the same ease; from whence it follows, that soft iron readily acquires a considerable degree of magnetism, but which is at the same time fugitive; while steel, magnetised with much greater difficulty, preserves its virtue longer; and it is for this reason that steel alone is used for making artificial magnets.

570. The most simple way of communicating magnetism to a steel or iron rod, is to rub this rod with a magnetised bar, gliding one of the poles of the bar along the rod through its whole length, and repeating several times this operation in the same direction. Suppose the pole in contact with the rod to be the

---

* Annales du Museum d'Hist. Nat. N. 5, p. 350.

boreal pole of the bar: the action of that pole attracts the austral fluid of the rod, and repels the boreal fluid; whence it results, that the part of the rod in contact with the bar, tends incessantly to the austral state of magnetism, and when the bar reaches the extremity, and is then taken away, the part it has quitted is in that same state of magnetism.

During its motion the bar acted at the same time on each part, at a certain distance, to repel the boreal fluid; but in proportion as it advanced towards the extremity where its motion was to end, it destroyed the effect of that action in the points it approached, and made them pass to the austral state of magnetism; whence it follows, that at the termination of its motion, the parts situated within a certain limit of the extremity which it came to quit possess austral magnetism, and the ulterior parts, situated towards the opposite extremity, have acquired boreal magnetism; and accordingly, when the rod shall afterwards be left to itself, the two fluids, to answer to the conditions of equilibrium, will be distributed in such a manner that all that half over which the bar last passed, will possess austral magnetism, and the other half boreal magnetism.

If a new friction be given in the same direction as before, it will partly diminish the effect of the preceding, and partly increase it: and so long as the second effect shall prevail over the first, the rod will continue to acquire magnetism. But this augmentation of the magnetic virtue will be so extremely limited, that after a few strokes the communication of magnetism will cease.

571. The method of double contact, invented by Mitchell, is much more advantageous. It is this: Take two magnetic bars, R, S, (fig. 72), and raise them vertically at a short distance from each other, so that

their opposite poles, A, B, may correspond. In this situation make them glide from one end to the other, backwards and forwards alternately, along the rod, B′ A′, that is to be magnetised, taking care that they never pass beyond either extremity of the rod. After a few strokes, when the bars are near the middle of the rod, take them away in their perpendicular direction to the rod. The result of this operation, is to place each extremity of the rod in the contrary state to that of the inferior pole of the bar, situated towards that extremity.

To understand the effect of this method, let us consider first, what passes in the part of the rod answering to the interval between the centres of action *a*′ and *b*′ of the inferior poles, the only ones which have any very perceptible influence on the result. It is easy to perceive, that each molecule of the austral fluid, such as *x*, comprehended in that intermediate part, is attracted from left to right by the boreal centre of action *b*′, and repelled in the same direction, by the austral centre of action *a*′. On the contrary, each molecule, *m*, of the boreal fluid is attracted from right to left, by the centre *a*′, and repelled in the same direction by the centre *b*′. These effects are contrary, as far as a certain point, from the influence which the bars exert on the ulterior parts; for example, the bar S repels towards the right the moleculæ, *y*, of the boreal fluid which are behind it, while it repels from right to left those which are before, in the interval between the centres. But the first repulsion is in a great measure destroyed by the contrary attraction of the other bar R, on the same moleculæ; so that every thing being counter-balanced, the operation goes on incessantly towards its object, which is, in general, to produce austral magnetism in the half of the rod situated to the right, and boreal magnetism in the opposite half. The precaution that is observed at the end of the operation, of taking away the bars when at the middle of the rod, tends to favour the symmetrical distribution of the fluids in the two halves of the rod when left to itself.

572. A consideration presents itself here relative to the distance requisite between the bars, that their actions may have the greatest possible influence on the principal effect, that is to say, on that which is produced in the space intercepted between those bars. The determination of this distance depends upon the height of the centres of action, *a*′, *b*′, above the bar A′ B′, which receives the magnetic virtue. To understand this, suppose that the bars, being at a distance from each other, have their centres of action in *a b* (fig. 73), and that A′. B′ be still the body that was to be magnetised. For the greater simplicity, let us confine our attention to the repulsive action of the centre *b* on a particle, *m*, of the boreal fluid contained in the bar A′ B′. This action being directed obliquely, with respect to the length of the bar, which is the direction in which the fluid must be impelled to arrive at B′, it decomposes itself into two other actions: one, answering to *b p*, perpendicular to A′ B′, is nugatory as to the proposed effect; the other corresponding with *b r*, drawn parallel to A′ B′ till it meets *m r*, perpendicular to the line joining the two centres; and this second force alone contributes to the motion of the particle towards B′.

Now, on the one hand, the line *b r* increases in proportion as the angle *b m a* is less acute, or, which is the same thing, in proportion as the two bars are farther from each other; but at the same time, the intensity of the action of *b* diminishes, by reason of the greater distance between that centre and the molecule *m*. Suppose this distance to be nothing, the action represented by *b r* will vanish; on the contrary, suppose it infinite, the intensity of the force *b* will become zero in its turn. There is therefore, with respect to the angle *b m a*, a certain mean measure, giving for the real force the greatest possible value. Æpinus, who supposed that the action of the magnetic forces followed the inverse ratio of the simple distance, found that the angle *b m a*, in the case of a *maximum*, was a right angle; but if the real law be established, that is, the law which follows the inverse ratio of the square of the distance, we shall have 70° 31′ 44″ for the measure of the angle in question[*].

Suppose, for example, that the bars employed in this experiment were in the same state as the steel wire of which we have before spoken (560), which was 67·5 centimetres in length, having the centres of action 22·5 millimetres from the extremities; to obtain the *maximum* of action, the bars must be placed at the respective distance of 32 millimetres.

573. Æpinus, in the method of double contact, has followed a different process, by inclining the bars in a contrary way, as is represented in fig. 74, pl. XI, so that each shall make a small angle of about 15 or 20

degrees with the bar A′ B′. By this mode of operating he supposes two things to be obtained: first, that the centres of action, a′, b′, which were raised to a certain height above the surface of the bar A′ B′, when the bars which acted upon it were in a vertical position, are in the present case much nearer to it, and their action becomes in consequence much more efficacious. Secondly, the interval between the centres of action being greatly augmented in consequence of the very obtuse angle which the bars make with each other, this new circumstance widens the limits between which the effect of the conspiring forces was compressed, and proportionally favours the activity of those forces (g).

But these advantages were in a great measure balanced by the inconvenience which attended the operation, of frequently producing in the bar A′ B′ consequent points, whose action, though slight to the senses, was not to be neglected; especially when the needles of mariners' compasses were in question, their perfection partly depending on the unity of their poles. To comprehend this inconvenience, let us suppose that the bars A B in moving from A′ to B′ are at the middle of the bar A′ B′. Let *r z* be a perpendicular let fall from the centre of action of A on this last bar.

(g) The method of double touch, or double contact, was first published by Mr. Canton, who availed himself of the ingenious experiments of Mr. Mitchell of Cambridge, to whom the discovery is justly ascribed by Haüy. The method here attributed to Æpinus, is due to Antheaume, and was described in his memoir *sur les Aimans artificiels*, 1766. According to Professor Robison, the great advantage of this method is the regularity of the magnetism which it produces. We never find more than two poles; and when the bars are hard and of uniform texture, the polarity is very little diffused, and seemingly confined to quite a minute space at the very extremities of the bar; which is a prodigious advantage in point of strength. This method too, appears the only one, by which two bars can be impregnated joined end to end, considering them as one bar.—Tr.

A molecule, s, of the boreal fluid situated to the right of this perpendicular is strongly solicited to approach it, by virtue of the action of the two bars A B; but at the same time a molecule, s', of the same fluid situated to the left of the same perpendicular is attracted in an opposite direction, and this action is no longer sensibly destroyed by the contrary force of the centre b', as in the case where the bars A B are situated vertically. Now it may happen that the fluid, s, s', shall be so accumulated in the space it occupies, that when the motion of the two bars shall afterwards be continued, the coercive force of the bar A' B' shall permit them only to repel back again towards B' a part of the same fluid. There will consequently be formed in the space $s\ s'$ a boreal pole, which in its turn will give rise to an austral pole in the next space situated towards B', and thus will introduce into that space a kind of perturbating force in regard to that of the extremity B'.

To remedy this inconvenience, Coulomb, having placed the two bars A B on the middle of the bar A' B', inclining them as Æpinus did, draws them in contrary directions to each other, till at a small di-

R, S, which are already in a magnetic state, are then used, to communicate the same virtue to one of the first bars, as M for example, following the method of Æpinus, or, if it be preferred, that of Coulomb. This bar acquires poles, the positions of which are indicated by the figure, and already the other bar N, by virtue of the communication that is established between it and the bar M, by the intermediation of contacts, receives itself a commencement of magnetism; and it is easy to conceive, that each of its poles corresponds to the contrary pole of the bar M, as may also be seen by the figure. After a certain number of strokes, the bar M is turned, without changing the disposition of its poles, and the operation is repeated on the other surface. Similar frictions are successively given to the two surfaces of the bar N, taking care to reverse the positions of the poles of the bars R, S, because those of the bar N are themselves situated in a contrary direction to the poles of the bar M. This done, the bars R, S, are substituted for the bars M, N, and the last are used to augment the virtue of the others. When the communication of magnetism is supposed to have attained its greatest extent, those bars which were last subjected to friction are preferred, to magnetise steel needles, and other bodies of the same nature.

The effect of this operation is favoured by making the other two bars concur as auxiliary means in producing it. In that case, those bars are directed on one and the same line, as represented in fig. 76, at a less distance than the length of the needle that is to be magnetised, and the needle has given to it the position *a b*, answering to the interval between the two bars, so as to rest upon them by its extremities.

If the bars M, N, (fig. 75), had already a certain degree of magnetism, it is evident that they ought previously to be placed in their respective positions analogous to those which the figure represents, where the poles of different names correspond on the same side.

575. Suppose that the bars M, N, were in some way or other to be kept in an invariable position, relatively to themselves and to one of the contacts T, and that, having suspended this apparatus vertically, so that the point at which it is held may be on the side of the fixed contact, there were to be placed on the side of the other contact a piece of soft iron with a hook below it, like that represented underneath the magnet P S (fig. 77). By suspending different bodies to this hook, we shall be able to ascertain the weight the magnet is capable of bearing by virtue of its attractive force. It is upon this principle that artificial magnets are constructed; all the difference is, that for the bars M, N, two bundles of thin steel laminæ are substituted, which, having before been magnetised separately, are then so united, that they might in each bundle be contiguous by the poles of the same name. Coulomb has formed magnets of this kind that weighed about ten kilogrammes, or twenty pounds, and of which the power was equivalent to a

We shall enter here into a few particulars respecting the armour of magnets and the communication of magnetism.

576. The name of armour is given to the plates of soft iron applied to natural magnets at the places of the poles, and that contribute either to preserve their virtue, or even to increase it. Previously to arming a magnet, it is shaped like the rectangular parallelopiped P S (fig. 77); so that if we conceive a plane passing at equal distance from the two opposite surfaces, and parallel to those surfaces, the two halves intercepted by this plane will be in two different states of magnetism, like those of a magnetised bar. Each armour, *f h* or *f′ h′*, has the form of a carpenter's square, of which one of the branches, *f f′*, which is longer than the other, and is called the *leg* of the armour, is applied to one of the surfaces we have mentioned; and the other branch, *h h′*, which is the *foot* of the armour, is applied to the adjoining surface, which may be considered as the base of the parallelopiped. Of this base the armour covers only a space a few millimetres in length.

Let us now analyse the effect of the armour which answers, for example, to the pole B of the magnet.

---

such a shaped piece magnetic, place a pair of magnetised bars against the ends of the horse-shoe, with the south end of the bar against that of the horse-shoe which is intended to be the north, and the north end of the bar to that which is to be the south; the lifter, of soft iron, to be placed at the other end of the bars. Also rub the surfaces of the horse-shoe with the pair of bars disposed like the legs of compasses when a little open, or with another horse-shoe magnet, turning the poles properly to those of the proposed magnet; and being careful that these bars never touch the ends of the straight bars. To prevent a sudden separation of the bars from the horse-shoe, which would considerably diminish the force of the latter, slide on the lifter, or support, to the end of the horse-shoe magnet, but in such a manner that it may not touch the bars; they may then be taken away, and the support slid to its place.—Tr.

The force of this pole acts so as to decompose the natural fluid of the armour; it attracts the austral fluid in the parts of the substance of the armour nearest the loadstone, and repels the boreal fluid in the parts most remote; and as it acts much more efficaciously on the leg *f*, the austral fluid will in preference pour itself into the substance of that leg, and the boreal fluid will be driven back in great measure into the foot *h*, as much by the action of the magnet, as by the mutual repulsive force of its own moleculæ.

The foot of the armour will accordingly acquire the kind of magnetism which exists in the corresponding part of the magnet, that is to say, boreal magnetism. By a similar mode of reasoning we may prove, that contrary effects take place with regard to the other armour.

Now the leg acts in its turn, by an austral magnetism, on the boreal pole of the magnet, to attract there a new fluid; an effect that is but weakly balanced by the opposite action of the foot of the armour, which is at a greater distance. By a necessary consequence the foot will acquire an increase of force; and it is, in general, to this combination of reciprocal actions that remainder of the thickness, would produce there a magnetism similar to that of the same pole, and of which the reaction on that pole would oppose itself to the principal effect. There is therefore, a certain degree of thickness that gives, relatively to the leg of the armour, the *maximum* of magnetism, contrary in kind to that of the adjacent pole, and relatively to the foot the *maximum* of magnetism similar to that of the same pole. The artist who would direct the construction of the armour, so as to give the greatest possible perfection to the magnet, must ascertain that degree; which he can only do by trials—as it were, by continual gropings in the dark (*i*).

4. *Magnetism of the Terrestrial Globe.*

577. The natural phenomena of magnetism, compared with those of electricity, exhibit one of the most striking differences between the modifications of the fluids which produce these two classes of phenomena, in other respects connected by the most prominent analogies. Those which belong to electricity are not very apparent but in local and variable circumstances, and have birth commonly in the midst of meteors, which have themselves only a transient existence. Magnetism exerts an action that is universal

---

(*i*) *Kircher*, in his book *de Magnete*, says, that the best way to arm a loadstone, is to drill a hole through it, from pole to pole, in which is to be placed a steel rod of a moderate length: this rod, he asserts, will take up more weight at the end, than the stone itself when armed in the common way: and Gassendus, as well as Cabeus, prescribe the same way of arming. But Muschenbroek found by repeated trials, that the usual armour, such as described by our author, is far preferable to Kircher's; and indeed instances are authentically recorded, in which such an armour has multiplied the natural intensity of the leadstone, a hundred, or even a hundred and fifty, times.—Tr.

and durable, that relates to all determinate points, that varies only by a slow and gradual progress, and that has its seat in the very globe that we inhabit. By its general nature it is become an unexhaustable source of observations, which are repeated in every portion of the seas. On this subject, every navigator is a philosopher, and does not cease to fix an attentive eye on that needle, which his presence seems to animate, and which can serve him as a guide in countries the most remote from his own.

578. Before we state the different opinions of philosophers as to the cause of natural magnetism, we shall explain what has been observed relative to the position of the magnetic needle. When it is said of this needle, that if it be suspended freely it will turn one of its extremities to the north, this is only true in a general sense, that admits of a great number of restrictions. If the needle be successively carried to different points of the globe, there will be some among them where its direction will coincide exactly with a line drawn from south to north, or with the meridian of the place. But in other points it will deviate from that line, sometimes to the east, sometimes

soon as it shall have received the magnetic virtue, it will assume a position more or less inclined with respect to that plane; except in certain quarters of the globe. To this second deviation the name of *inclination* has been given.

580. If we set out from one of the places where the needle has no declination, and advance either towards the north or the south, we shall pass over a series of points where there will in like manner be none: but these points will not be all on the same meridian; they will form an irregular curve that will have inflections different ways.

581. Halley is one of the first who has undertaken to trace on a map of the world these series of points, where the declination is zero, and which have been denominated *zones of no declination*.

Hitherto three such zones have been observed, which mariners have traced to latitudes more or less considerable.

582. Further, the declination varies with time in the same place, but the variations do not increase in the same proportion as the time; so that the zones of no declination change continually both as to position and figure. At Paris there was no declination in 1666; but 12 Floreal of the year 10, that is, 136 years afterwards, Bouvard found it to be 22° 3′ towards the west (*k*).

583. It also happens, that the declination is sometimes subject to interruptions, so that the needle manifestly remains stationary for a while. For example, at Paris the needle experienced no alteration from the

---

(*k*) At London the declination in 1580 was $11\frac{1}{4}$° east; there was no declination in 1657; and in 1793, that is, 136 years afterwards, the declination was nearly $24\frac{1}{3}$° west.—Tr.

year 1720 to 1724, during which it was constantly at 13° from the meridian.

584. Observation proves also, that the variations of the declination compared with one another in different points of the globe, follow different relations. But there is a fact extremely worthy of attention, that has been remarked by the celebrated Hallé, on the mere inspection of the table of declination published by Van Swinden, whose notice it had escaped. In the table, three places are pointed out, where the needle has experienced the greatest declination: and these are, first, in the middle of the Indian ocean, from 10° to 15° of south latitude, and from 82° to 87° of east longitude (reckoning from the isle of Ferro), where the variation, from the year 1700 to that of 1756, was from 11° to 11° 15′. Secondly, in the Æthiopian ocean, from 5° of north to 20° or 25° of south latitude, and in the interval of 10°, 15°, and 20°, of east longitude; the variation relative to this space, during the same period of time, was from 10° to 10° 45′, principally under the line and to 5° southward. Thirdly, at 50° north latitude, and between 17° of east and 10° of west longitude; where again, in the

Bermuda islands. And here also we must remark, that in the ocean between Africa and North America, the variation is much less towards the American than towards the African coasts. Secondly, the environs of the isle of Madagascar, and part of the coast of Zanguebar. Thirdly, that part of the ocean which is to the south and south-east of the Sunda islands, between those islands and New Holland. And lastly, in the same sea, about the 4th degree of south latitude and the 97th of east longitude, that is, in the middle of the space comprised between the western angle of New Holland and the southern point of Africa. In all these different places the declination of the needle has not varied, during the whole 56 years, so much as one degree *.

If similar observations had been made in the Pacific ocean, in the northern and southern oceans, and even the principal divisions of large seas, such as the Baltic, the Mediterranean, the Gulf of Mexico, &c. these places would probably have furnished similar points: and how greatly would the study of natural magnetism be facilitated, by referring a series of such facts in subordination to a number of centres, round which they would range themselves according to the order of their respective relations!

585. The magnetic needle is also subject in certain places to a particular diurnal variation, the course of which has been watched by Van Swinden with that constancy and attention which characterise this excellent observer. The law of this variation is such, that in general the needle deviates towards the west in the morning, till the hour of noon, or a little after; to return again in the evening towards the east.

This double movement is subject to four modifica-

---

* Encyclop. Méthod.; Medicine, second part, vol. I. p. 418.

tions. The first takes place when the needle advances progressively, during the morning, towards the west till it attains its *maximum*, and then returns in one direction only towards the east during the evening, thus performing a single period, which may be represented by the initial letters, W, E. In the second modification, the needle first approaches a little towards the east in the morning; and this little motion is succeeded by the ordinary period; so that its complex course may be represented by *e*, W, E. The third modification is that in which the usual period is followed, towards the close of the evening, by a small movement towards the west; the total motion being in that case represented by the initials W, E, *w*. Lastly, the fourth modification partakes of both the second and the third; and may be expressed by *e*, W, E, *w* *. Thus, therefore, the needle performs continual oscillations, whose general result is such, that the sum of the motions that take place towards the west prevails over that of the motions in the contrary direction; so that the declination westward continues to augment.

586. Nor is this all; for these variations, which, in

often when an aurora borealis appears*. But the immediate influence of these phenomena, considered as causes of the perturbation of the needle, has not hitherto been ascertained.

587. The inclination of the needle has also its variations, which are especially manifest on a change of latitude. At the equator it has scarcely any variation, so that all the points where the needle is exactly parallel to the horizon form an irregular curve that cuts the equator at very small angles. In proportion as we depart from this circle, towards either pole, the inclination increases, so that the extremity of the needle turned to the nearest pole continually sinks below its first position. The greatest inclination that has yet been mentioned is one of 82 degrees, observed by Phipps in 79° 44′ south latitude, and 131° longitude. At Paris, in 1787, the inclination was 71 degrees: but it also varies with time in the same place. To remedy the effect of this variation, at least during a certain number of years and relative to the same point of the globe, a greater weight is given to one half of the needle than to the other, in such proportion, that the force drawing one end of the needle downwards may be compensated by the superior weight of the other end, and the needle thus be able to preserve an horizontal position.

588. From the whole of these observations, philosophers have concluded that the terrestrial globe performs the office of a real magnet. Some have even attempted to ascertain the cause of its magnetism; by means of certain hypotheses which we shall presently state. But previously to this, it will not be entirely

---

* Reçueil de Mémoires sur l'Analogie de l'Electricité et du Magnetisme, by Van Swinden, vol. I. p. 466, and vol. III. p. 187, et seq.

useless to explain a few particulars relative to the general idea, that the globe acts in the manner of magnetic bodies.

Let us imagine for a moment, that the two centres of action, which result from all the forces exerted by the globe, have fixed positions on its axis, at equal distances from the poles; and further, that their actions are respectively equal (*l*).

On this supposition, a magnetised needle will constantly take a direction that will coincide with the meridian of the place where it is; that is, there will be no declination in any part of the globe. If the needle be taken to the equator, it will assume a direction parallel to the axis; in other words, there will then be no inclination.

Let S G T F (fig. 78) be the circumference of one of the meridians, S T the axis of the globe, and B, A, the two centres of action. Suppose the needle to be placed above the point O at the distance of 90 degrees from S and T; it will evidently take the direction *a b*, parallel to the axis.

But if the needle depart from the equator, for example, towards the north, S, it will take an inclined in the line $a' b'$, parallel to S T, but in the line $a'' b''$ [*], the obliquity of which will continually increase, as the needle approaches the pole S; where it would even have a limit, the direction of the needle forming there a right angle with the axis S T. By which it appears, that the different positions which this needle would take in moving from the equator to the pole, would form a curve analogous to that we have mentioned (557) when analysing the action of a magnet on the needle, which received a slight continuous movement according to the tangent of the arch before described.

589. But the supposition we have been making is only so far applicable to the mode of action of natural magnetism, as the modifications which the results of observation require are given to it. Things take place here as if the different points of the globe had almost all their particular poles. Its inclination no longer follows the same law, as in the case where the magnetic axis was confounded with the axis of the globe, and had its centres of action equal in force, and situated at equal distances from the poles. In short, the magnetic axis appears to change of itself its position with time, relatively to every point of the globe.

590. If we leave out of our statement the hypotheses which, to explain these discordant effects, have recourse to vortices of magnetic matter, that turn round the globe, entering at one pole and issuing out at the other, and the hypotheses of effluvia, which, departing from the equator, proceed towards the poles by contrary movements, there will remain two different opinions, respecting the cause of natural magnetism, for us to consider.

---

[*] If the direction of this line were parallel to the horizon G F, of the point Z, with which the needle corresponds, there would be no inclination: this is really the case in some places, but every-where else the needle sinks towards the horizon of the place.

Some philosophers have had recourse to the influence of magnetic mines, which they suppose to be very abundant near the poles. The diversities that are observed for an instant only in the declination and inclination of needles situated in different parts of the globe, they ascribe to the irregular disposition of the masses of which these mines are formed; and the successive changes which the mines undergo, from the influence of divers causes, that alter or destroy their effect in one place, while they revive it in others, occasion, they suppose, the declination and inclination to vary, in their turn, with time, relative to each particular place.

591. Halley, Æpinus, and others, without denying the influence of magnetic mines on the direction of needles, have regarded it only as a secondary power, and have supposed the principal force to proceed from a large magnet, of a globular figure, or nearly so, forming as it were the nucleus of the terrestrial globe. Halley also imagined this nucleus to have a very slow motion, by which its position as to the globe was continually changing; which tended, in his opinion, to explain the variations occasioned by time in the declination and inclination of needles, relative to the same place.

592. Æpinus does not admit of this motion, which appears to him to be insufficient for the purpose intended, and even perfectly useless; to reconcile the phenomena to the hypothesis of the fluid nucleus, he observes, first, that if the fluid were distributed uniformly in this nucleus, so that its two centres of action, having equal force, might be situated, in regard to the axis of the earth, at equal distances from the centre, there would be no declination at any point of the globe; while the inclination, disappearing only at the equator, would increase towards the poles, conform-

ably to some law depending upon the change of latitude.

But the distribution of the fluid is not regular in the interior of the nucleus. In some parts the accumulation of fluid is greater, in others less; and it follows from this, that the positions of the centres of action change continually in regard to a needle taken to different points of the globe. If the point to which the needle really answers is so situated, that the resultant of all the forces, which act differently at different points of the magnetic nucleus, is parallel to the axis of the earth, there will be no declination; and accordingly as this resultant shall form an angle with the axis of the earth more or less obtuse, the declination itself will be greater or less.

In another view, the distribution of the fluid changes with time in the interior of the nucleus; and by these changes, those which the declination and inclination experience in the same place, are determined.

593. With regard to the diurnal variation observable in the declination of the needle, Mr. Canton has supposed that it may be explained by the diminution of attractive force which the solar rays must occasion in the magnetic nucleus of the globe. This diminution taking place in the morning, relative to the eastern parts of the globe, the needle, less attracted there, must decline towards the west; and in the latter part of the day the contrary must be the effect.

594. An experiment made by Lahire has given fresh colour to the hypothesis we have been speaking of. This philosopher, having shaped, in the form of a sphere, a natural magnet that weighed nearly a hundred pounds, and determined its axis, by the position of the magnetic poles, traced on the sphere an equator, and a certain number of meridians. He then made a magnetised needle to correspond successively

with the different points of that magnet, and he remarked, that at some of those points it took a direction precisely from pole to pole, and in others declined either to the right or the left, the greatest declination he observed being about 26 degrees.

595. Such was the state of our knowledge as to this subject, when Coulomb, on whom the task seems to have devolved of estimating those very small forces discoverable only by the most delicate attention, was led, by similar experiments, to unforeseen results, that have diffused new light over this branch of philosophy. This excellent philosopher took two magnetic bars, which he so disposed on a right line that their opposite poles were about 25 millimetres from each other. In the intermediate space he placed successively a number of small cylinders, made of different materials, and from seven to eight millimetres in length. Each cylinder was suspended freely to a silk thread, such as it comes from the silk-worm. Coulomb observed, that this cylinder, of whatever material it was composed, always arranged itself exactly according to the direction of the bars, and if it were moved out of that direction, it invariably returned to it again, after a certain number of oscillations. Gold, silver, copper, lead, glass, chalk, the bones of animals, and different kinds of wood, were tried, and all these bodies felt the action of the magnetic bars *.

Two ways suggested themselves of explaining these phenomena: the first by supposing that all the elements which enter into the composition of our globe were by their nature susceptible of the magnetic virtue, but that in most bodies it is so trifling as to be nearly nugatory; and has scarcely been observed except in iron, which possesses it in an eminent degree.

---

* Journal de Phys. Floreal, year 10, p. 367, et seq.

The other explanation supposed that the magnetic action exerted by the bars, in the experiments we have cited, was owing to moleculæ of iron pervading in an imperceptible manner the different natural substances, and eluding the strictest investigation of chemical analysis. Coulomb, who was favourable at first to the former explanation, appears to have wavered since between the two, and has devised a set of experiments, which he has in part already executed, the object of which is to measure the action of the bars on the different bodies, and ascertain, relative to the mass of each, what quantity of iron must be disseminated in its interior, to produce the number of oscillations made in a given time.

However that may be, the fact we have stated is the more interesting, as it leads us to consider the terrestrial globe, taken in its whole extent, as an entire magnet, the force of which is the aggregated amount of all those exerted by the moleculæ that enter into its composition. This fact being once fully established, with regard to all terrestrial bodies, would advantageously compensate for the hypothesis of an individual magnet nucleus, which has the air of having been invented by naturalists rather to support their own theories, than to give a fair representation of nature (*m*).

(*m*) Professor Ritter, of whom we have spoken in the notes on Galvanism, has recently communicated to the Royal Academy of Sciences at Munich, an account of a series of experiments referring directly to the nature of magnetism: from these he infers that the terraqueous globe is a great magnet; he also shews a remarkable connection between magnetism and Galvanism which we cannot forbear mentioning here.

The following are the results of the experiments of Ritter, as abridged by Professor Millin in his Magasin Encyclopédique for May last (1806).

1. Every magnet is equivalent to a pair of heterogeneous metals united together; its different poles represent as it were different metals.

2. Like them, it gives electricity; that is to say, one of the two poles, the positive electricity, and the other the negative.

We shall remark here, that M. Prevost had previously asserted, that to explain natural magnetism, it was not necessary to have recourse to the supposition of a particular nucleus. It is sufficient, according to this naturalist, that the decomposition of the fluid, which is only effected in the interior of the iron, by means in our own power, may have place even out of that metal from natural causes more powerful than the agents of art, and whose permanent influence would keep the two poles of the globe in two states of opposite magnetism *.

596. On the hypothesis of all bodies possessing the

---

3. By following the same process, a certain number of magnets, as well as a certain number of pairs of metals, afforded electricity; and in this manner the electricities afforded by the poles of different magnets, have been successfully indicated by the electrometer.

4. By means of these electricities, one of these batteries of magnets, accordingly as it is more or less strong, produces upon dead and living bodies, all the phenomena which are produced by a Voltaic pile of the usual kind, and of the same force.

5. The experiments which prove this, shew, that in magnetised iron the south pole gives positive electricity, and the north pole negative electricity; but that on the contrary in magnetised steel, the north pole affords the positive electricity, and the south pole the negative.

6. The same inverse disposition is also observed with regard to the polar oxydability of the magnetised body in which this change is produced by magnetism. In magnetised iron the south pole is most oxydable, and the north pole least; whereas in magnetised steel the north pole is most oxydable, and that of the south least.

7. Mr. Ritter thinks, that by considering the earth as an immense magnet, these results might serve to explain various phenomena of nature, such as the physical difference between the two hemispheres, the aurora borealis, and the aurora australis. In fact, after what has been just stated, the earth, considered as a magnet, may be taken as an equivalent to a vast Voltaic pile whose poles are on one side sufficiently closed by the waters of the ocean. And the action of this pile must have produced the greatest chemical changes in the materials of the earth; changes which will have differed according to the poles; and of which pile the poles at the other extremity have always such an abundance of electricity as to cause its splendour to appear by radiations in the heavens.—Tr.

* De l'Origine des Forces Magnetiques, p. 200, et seq.

property of magnetism, whether of themselves, or by virtue of ferruginous moleculæ disseminated in their interior, the actions resulting from this property would necessarily be variable, from the different nature of those bodies: and it appears as if the same effect ought to follow here, as on the supposition made by Æpinus, of an unequal distribution of the magnetic fluid in the nucleus supposed by that philosopher to be seated in the centre of the globe. And it would therefore be difficult to conceive, that the deviations of the magnetic needle should follow a law capable of being ascertained by us. Yet some philosophers have imagined themselves to have discovered this law, and have referred it to a kind of progression, which the quantity of declination relative to every point of the globe ought to afford. They have even gone so far as to pretend, that the declination might serve to resolve the problem of the longitude: but we are, as yet, far from possessing observations either sufficiently numerous or sufficiently precise to know whether the variations of the magnetic force are capable of being represented by any formula; and we may truly say, that in this respect the science of magnetism is not yet matured sufficiently to admit of the application of geometry (*n*).

(*n*) Since the publication of M. Haüy's Treatise, a memoir has been presented to the French National Institute by *Humboldt* and *Biot*, "On the Variations of the Terrestrial Magnetism in different Latitudes." These philosophers have first determined the position of the magnetic equator *by direct observations*, which had never been done before; they have also proved that the magnetic force increases in proceeding from that equator to the poles; and lastly, they have given a mathematical hypothesis which when reduced to a formula accords with all the inclinations of the needle hitherto observed. In regard to the declination and intensity, they freely confess that they are entirely unacquainted with their laws and their causes.

1. As to the position of the magnetic equator, supposing it to be a great

It is possible, notwithstanding, to explain in a general way, by means of acquired knowledge, many remarkable appearances that magnetism exhibits. We shall begin with such as relate to needles that are themselves already in a state of magnetism; and shall then proceed to those which depend on the action that the globe exerts on ferruginous needles and rods, by

---

circle of the terrestrial sphere, an hypothesis which is conformable to observations: the inclination of this plane to the astronomical equator, is equal to 12·2025° of the decimal division (10° 58′ 56″ of the common division), and its occidental node on that equator is at 133·3719° (120° 2′ 5″) longitude west from Paris, that is, a little beyond the continent of America, near the Gallipagos in the South sea; the other node is at 66·6281° (59° 57′ 55″) eastward of Paris, that is to say, in the Indian seas. The points where the axis of the magnetic equator pierces the earth's surface, are, the northern point at 87·7975° (79° 1′ 4″) of north latitude, and at 33·3719° (30° 2′ 5″) of longitude west from Paris,—the southern point is situated in the same latitude south, and 166·6281° (149° 67′ 55″) of longitude east from Paris. It is remarkable that this determination of the magnetic equator agrees almost perfectly with that given 40 years ago by Wilke and Lemonnier. Can it be by chance that these elements found so long ago should accord so well with those determined from recent observations? Or, does the inclination of the magnetic equator experience only very small variations, while all the other symptoms of terrestrial magnetism change so rapidly? Humboldt and Biot incline to the latter opinion; and this because the inclination of the magnetic needle has changed at Paris only 3° during performing, in regard to them, the same function as ordinary magnets, to which other bodies of the same kind are presented, that were previously in the natural state.

To apply the theory, nothing more is necessary here, than to suppose, that a given point of the surface of the globe has a particular magnetic axis,

needle employed in one of his previous aërial excursions, he found that its tendency to return to the magnetic meridian was constantly stronger in those mountains than it was at Paris before his departure, and than it had been since his return. This needle, which made at Paris 83·9 oscillations in 10 minutes of time, gave oscillations as below at the places mentioned, in the same interval of 10 minutes: viz. Paris, before departure, 83·9; Turin, 87·2; on mount Genêvre, 88·2; Grenoble, 87·4; Lyons, 87·3; Geneva, 86·5: Dijon, 84·5; Paris, after his return, 83·9. It appears to result from these observations that the action of the Alps has a perceptible influence on the intensity of the magnetic force. Humboldt observed analogous effects at the bottom of the Pyrenées, for instance, at Perpignan. It is not improbable that they arose from the mass of these mountains, or the ferruginous matters contained in them: but whatever may be the cause, it is hence manifest that the general action of terrestrial magnetism is sensibly modified by local circumstances, the differences of which may be perceived in places very little distant from each other.

3. In order to determine the law that regulates the inclination of the needle, Biot supposed in the axis of the magnetic equator, and at equal distances from the centre of the earth, two centres of attractive forces, the one austral and the other boreal, so as to represent the two opposite magnetic poles of the earth: he then calculated the effect which ought to result from the action of these centres upon any point of the earth's surface, assuming the attractive force in the reciprocal ratio of the squares of the distances: he found that his results approximated more and more to the truth in proportion as the distance between the magnetic poles was assumed less; and indeed, by supposing those two poles or centres to coincide, or the inclination of the magnetic needle to be produced by an indefinitely small magnet placed in the centre of the earth, his theorem gave the same numbers as had been observed by Humboldt both in Europe and in America, as well as what had been observed in Russia, Lapland, and various other places in both hemispheres: the results of theory being classed with those of observations in a comparative table, which clearly evinces their near coincidence. Let u be the angle included between a radius drawn from the earth's centre to any assumed point on its surface and the magnetic axis, β the angle comprehended between the line coinciding with the real position

whose centres of action are at an extreme distance from that point.

597. Let us conceive A B (fig. 79) to be the magnetic axis relative to the point *o*, situated in the same vertical plane, and that there is in this point a molecule of austral fluid: that fluid will be attracted in the direction *o* B by the boreal pole of the magnetic axis, and repelled by the austral fluid according to the line A *o*. Let us represent by *o s* the quantity of attraction, and by *o r* a prolongation of A *o*, the quantity of repulsion, and then complete the parallelogram *o r k s:* the molecule will tend, by virtue of the two forces that solicit it, to move in the direction of the diagonal *o k* of that parallelogram. Let us suppose in the same point *o*, a molecule of boreal fluid: by means of a similar construction, we shall have the repulsion which the pole B exerts on it represented by *o z*, a prolongation of B *o*, and equal to *o s;* and the attraction which the pole A exerts, by *o x*, equal to *o r*. Then if we complete in the same manner the parallelogram *o z h x*, the motion of the molecule of boreal fluid will be according to the diagonal *o h*, which is evidently a prolongation of the other diagonal, and is

of the needle and the said magnetic axis, and I the inclination of the needle with the horizon of the place; then we have

$$\text{I.} \qquad \tan.\ \beta = \frac{\sin.\ 2u}{\cos.\ 2u + \frac{1}{3}}:$$

whence β is readily determined; and then we shall have the inclination by means of the following;

$$\text{II.} \qquad I = 90^\circ + u - \beta.$$

Still it must be observed, that though these formulæ given by Biot, furnished in general results very near the truth; yet when he attempted to represent the inclinations in different latitudes by the supposition of a magnet infinitely small, very near the centre of the earth and perpendicular to the magnetic equator, he did not pretend to consider the hypothesis as any thing real, but solely as a mathematical abstraction useful in connecting the results, and tending to ascertain in future whether any changes exist.—Tr.

besides equal to it; so that the two moleculæ will tend to pass through these two diagonals in the same time.

If we consider the action of the poles A, B, on other moleculæ of the fluid near the molecule *o*, and situated in the plane B *o* A, it is easy to perceive that they will be solicited so as to move in directions parallel to *k k*. It is in consequence of this, that, the poles A, B, being at an almost infinite distance from the moleculæ compared with that of the moleculæ from one another, the different lines in which the actions of the two poles exert themselves are supposed to be confounded.

We hence conclude, that if a magnetised needle be placed in the direction *k k*, it will continue immoveable there; and if it be afterwards placed in a different direction, but which has a common point with the line *k k*, as soon as it shall be free it will resume its first position.

In this position it is evident, that two points of the needle situated at equal distance from the extremities are equally attracted in a contrary way by the actions of the two poles; which we know to be conformable to the observation that tells us, that the forces which, in its freely suspended state, attract a magnetised needle towards the north, are equal to those which solicit it towards the south (543).

598. Let us suppose that the needle *a b* (fig. 80), being first in the direction *k′ k′*, the same as that of *k k* in the preceding figure, it were made to assume another direction, *g u*, so as to form still the same angle with the horizon. Let us imagine a plane passing through the lines *a b*, *g u*; and let us draw from the point *g*, in the same plane, the line *i g*, parallel and equal to *o k′*: the line *i g* will represent the resultant of the forces which act upon the point *g* to

bring it towards the point *a*. Now the force answering to *i g*, is resolvable into two others, the one, *i p*, parallel to *o g*, and the other, *i e*, perpendicular to *o g*. Therefore, if we complete the parallelogram *i p g e*, the line *p g* will represent the portion of the force *i g* that acts directly to impel the point *g* toward the point *a*. On the other hand, let *l u*, parallel and equal to *o h′*, be the resultant of the forces that exert themselves obliquely on the point *u*, to bring it towards *b*. By means of a similar decomposition, the line *u t*, perpendicular to *o t*, will represent the portion of the oblique force *l u*, the effect of which is to impel the point *u* towards the point *b*.

Now, since the forces which act on the needle, all concur to make it turn the same way, in order to regain its first position, we may consider them as being applied to the point *g* of the needle, by doubling, in idea, the intensity of the actions answering to *i g* and *i e*. In this case, *i g* will represent the resultant of all the forces by which the needle is solicited, taken parallelwise to the direction *a b*, which coincides with the magnetic meridian; and *i e*, or *p g*, will represent the directing force. But it is easy to perceive, that

599. What we have just said, may serve to reconcile an apparent contradiction exhibited by the action of the globe compared with that of ordinary magnets. If we put a magnetic needle on a thin piece of cork, so that it may swim above the surface of the water, in a vessel sufficiently large, and place at a certain distance a magnet, even of a moderate force, that has one of its poles turned towards the vessel, the action of this magnet will produce two effects: first, the needle will so direct itself, that if it be the boreal pole of the magnet that is nearest the vessel, it will turn its austral pole towards the magnet; and as often as the position may be deranged, no sooner is it left to itself than it will return to it. At the same time, it will advance to the edge of the vessel to approach as nearly as is possible to the magnet. Now, if we repeat this experiment towards the north, for example, by leaving the globe alone to act on the needle, the needle will be in the state of a magnet, that has a stronger action exerted on its boreal, than it has on its austral pole; the needle also will direct itself so as to turn its austral pole towards the north, and if its direction be changed, it will spontaneously resume it; yet it will make no motion towards the north, but will remain stationary on the water in the place where it was first posited.

This diversity in the results of the two experiments proceeds from the circumstance of the centres of action of the globe being, as we have before observed, at an almost infinite distance from the needle; whence it follows, that the difference between the forces acting on the needle, to draw it two opposite ways, is evanescent as to sense; and accordingly the tendency of the needle to translate itself towards the north, which depends on that difference, must in like manner be nugatory. Now the same circumstance does not take place, when a magnet is employed, that acts on the poles of the needle at distances that may be compared with one another: in that case, the difference between the two actions becomes appreciable, and there results from it a boreal action, that determines the needle to advance towards the magnet. In another view of the subject, we have seen, that the globe exerts on a magnetic needle, *g u* (fig. 80), to restore it to its first direction, conspiring forces, as *i e*, and *t u*; and here the greatness of the distance does not prevent those forces from preserving a sufficient degree of intensity to produce their effect.

We have now to consider the phenomena in which the comparison holds between the globe and such magnets as we can manage, relatively to the faculty possessed by the latter, of communicating the magnetic virtue to iron placed within their sphere of activity. Just so, the action of the globe, which extends through space to immense distances, is capable of producing a certain degree of magnetism in iron rods and other similar bodies, whose coercive force is not sufficient to resist that action.

600. Let us here call to mind what has been said (597) of this same action on two moleculæ, one of a boreal, and the other of an austral fluid, to make the first move in the direction *o k* (fig. 79), and the second in the direction *o h*. As the communication of magnetism is ascribable to similar movements taking place in all the magnetic moleculæ in the interior of an iron rod, it is evident, in the first place, that the most favourable position for the rod to acquire the highest possible degree of magnetism, is that which coincides with the direction *k h*. If we next suppose that the rod, continuing in the same plane, B *o* A, takes another position, such as *m n* (fig. 81); and if we consider the lines *o k*, *o h*, which coincide with the same

direction, as the resultants of the forces exercised by the globe, when the position is most advantageous, it will be necessary, in the present case, to decompose the force ok in two directions, one kx perpendicular to om, which does not contribute to the effect, the other ox, coinciding with om, and representing the real force; that is, that the force ok be diminished in the proportion of ok to ox. If we decompose in like manner the force oh in two directions, one, hl, perpendicular to on, and the other, ol, that confounds itself with that line, ol will represent the force acting alone to produce the effect required.

In proportion as the rod shall remove from the position mn, by assuming the direction pr, which forms a still more obtuse angle with the first, the quantity of real force, os, or og, will continually diminish; and when the rod shall be situated on the line tz, that forms a right angle with kh, the real force will be reduced to zero.

Beyond this term, if the angle which the new position of the rod forms with kh be augmented, so, for example, that the new position may coincide with bd, the same effects will begin again; that is to say, if we draw the lines kf and gh perpendicular, one to od, and the other to ob, of will represent the force which determines the motion of the austral fluid towards d, and og that which solicits the boreal fluid towards b.

If the rod be placed in a different plane, and not in BoA (fig. 79), it is easy to conceive that its most favourable position, relatively to this second plane, will be that in which its direction shall make the smallest possible angle with the line kh; and that the acquired magnetism will again be zero, when the length of the rod, by remaining in the same plane, shall form a right angle with kh.

601. These different results may be verified by an experiment as curious and simple, as it is easy to perform. You take a bar of soft iron and hold it in one of the positions in which it is capable of receiving magnetism from the action of the globe. The most favourable position at Paris, is that which has an inclination with the horizon of about 72 degrees, because this is the position that a needle would naturally take, that should have its two halves of equal weight, and should be moveable about an axis at its centre of gravity; but the vertical position will sufficiently answer in the experiment. The rod then being situated in this manner, you present its lower extremity to the austral pole of a magnetised needle placed on its pivot, and you perceive that it repels that pole. You then lower the rod, still keeping it in the same direction, till its upper extremity be opposite to the same pole of the needle, and there attraction will be manifested. You reverse the position of the rod, and immediately the poles themselves become reversed. The extremity which repelled the austral pole of the needle attracts it, and that which attracted repels it. Soft iron yielding but a very slight resistance to the internal motion of the two fluids, that disengage themselves from the natural fluid, the magnetic virtue it acquires is but a transient effect, that, by simply reversing the rod, gives place to a diametrically opposite one. These alternate and sudden changes from attraction to repulsion have an air of legerdemain, which tends to excite the suspicion of juggling on the part of the philosopher; so that the beauty of this experiment is in a great measure lost on the spectators.

Similar effects may be produced with a simple key, or any other body made of soft iron and that has an elongated form. But if the body have but little bulk, you must use a needle so slightly magnetised, that its immediate action on that body does not disturb the action of natural magnetism.

We may vary this experiment in the following manner. Having placed the rod in a vertical position, let its lower extremity be brought within such a distance of the austral pole of the needle that the repulsion begins to shew itself, and no nearer. Keep the lower extremity of the rod in the same position, while you turn the rod gently round the same point, in a plane perpendicular to the direction of the needle. Presently the repulsion will diminish, so that the needle will approach towards the rod, and resume at last its natural position, which will be at the moment when the rod shall be situated at right angles with that direction. If you then continue to turn the rod, the needle will be carried towards it from the effect of the attraction that will succeed to the repulsion; and by giving a slight degree of oscillation to the rod on each side of the position where its action was nugatory, we shall see the needle itself assume an oscillating motion, by which it will alternately recede from and approach the extremity of the rod.

602. Æpinus has remarked, that if we strike a number of times with a hard body a rod of iron held in a favourable position, the action of terrestrial magnetism with respect to that rod is thereby assisted. The shocks, given to the rod by these percussions, occasion in its mass a kind of general vibration, that displaces in a slight degree the particles, and, by diminishing their coercive force, facilitates the disengagement of the two fluids, and their motion towards the two extremities of the rod.

It is owing probably to a similar mechanism that we succeed in magnetising needles that were before in the natural state, or in reversing their poles if they were already magnetised, by subjecting them to a strong electrical commotion.

603. Philosophers have availed themselves of the slight degree of magnetism which the simple action of the globe produces in a rod, to solve the curious problem, *of being able to magnetise steel bars even to saturation, without having had previously any magnet in their hands.* It is merely necessary, first, to make bars of soft iron acquire an incipient virtue, by placing them in a convenient manner, relatively to the magnetic meridian of the place. Those bars are afterwards employed to magnetise others of a harder nature, which is done by friction on their surface. These again, in their turn, perform the same function as to other bars; and by a method similar to what we have mentioned in treating of the communication of magnetism (571), the force of the bars in question is increased even to its *maximum.*

604. The preceding details may serve to explain certain facts, that at first were calculated to excite a considerable degree of surprise; such, for instance, as the magnetism that is naturally acquired by bars of iron which have a fixed position over the summits of edifices. One of the first observations that has been mentioned of this nature, is that of Gassendi, respecting the piece of iron that supports the cross over the clock of St. John's at Aix in Provence. But other philosophers since have made the same observation relative to other bars of iron similarly situated.

There is perhaps no region of natural philosophy that shews so completely as the one we are contemplating, how much the ideas connected with any science extend and magnify themselves, in proportion as that science, in the stages of its progress, advances towards perfection. A magnet was formerly considered as a kind of wonder; and now we learn from observation, that all those instruments of malleable iron which we have perpetually before our eyes and in our hands, are kept in an habitual state of polar magnetism by the influence of the terrestrial globe. Their poles alone are variable, and reverse themselves continually from the changes to which these bodies are every instant liable. With regard to steel instruments, that, from their great coercive force, are more capable of resisting the action of the globe, to communicate the magnetic virtue to them, even there that action does not fail of its effect, when seconded by particular circumstances. Thus files, scissars, and other instruments, which are exposed to friction, shocks, or percussions, capable of giving play to the moleculæ of which they are constituted, pass gradually to a state of magnetism, and possess the power of raising particles of filings and even of iron wire of a small bulk.

Magnetism of Iron Mines.

Mines of iron, diffused in the interior parts of the globe with an abundance proportionate to the utility of this the most precious of all metals, have been the subject of various observations, that furnish a confirmation of the principles we have established, relative to the manner in which the magnetic forces act.

605. It has sometimes been observed, that pieces of magnet taken from the earth, and left in the same position in which they were found previously to their being extracted, have had their poles in a direction the reverse of what ought to have been the case, on the supposition of their having acquired their magnetic virtue either by the action of a magnet placed in the centre of the globe, or by that of the globe itself, considered as performing the function of a mag-

net. To remove the difficulty that appears to follow from this circumstance, it is simply necessary to suppose with Æpinus, that there are naturally formed in magnetic mines *consequent points*, analogous to those which are sometimes observed respecting iron magnetised by the ordinary processes (565). Hence we may perceive how it happens, that, when we detach a piece of magnet from the mine in which there are a series of consequent points, the separation has the effect of causing the poles, which terminate the detached piece, to turn in a different way from those belonging to other pieces magnetised in the usual method.

606. The ferruginous mine that has two magnetic poles, mineralogists have considered as a particular species, which they have denominated the *magnetic mine*: this was the *ferrum attractorium* of Linnæus. Among other mines, those which have not distinct poles, but the faculty merely of being attracted by the magnetised bar, they call *ferrum retractorium*; and those which do not yield to the action of that bar, *ferrum refractorium*. Delabre announced, in 1786, that the specular iron of Volvic, of Puy-de-Dôme, and of Mont-d'Or, had very manifestly two poles *; and we have heard of a similar observation respecting an octaëdral crystal either of Swedish iron, or else of some other country: but it remained a subject of surprise to see so many other bodies, which, although they contain a certain portion of iron in the metallic state, had remained so long in the bosom of the earth, without appearing to have partaken of the action that had converted the former into magnets.

---

* Journal de Phys. 1786, p. 119, et seq. Romé de Lisle had said the same thing before of a mine of specular iron at Philadelphia. Cristal. vol. III. p. 187, note 35.

607. We have lately undertaken a series of experiments with the view of throwing some light on this point of natural philosophy; but we considered, that if we used a bar of a certain force, as is commonly done to try the magnetism of ferruginous mines, it might happen, that bodies which were only feeble magnets might attract indifferently both poles; because, if we were to present, for instance, the boreal pole of the body respecting which we were making the experiment, to the boreal pole of the bar, the force of the bar might destroy the magnetism of the other body, and even cause it to acquire the contrary state, which would change repulsion into attraction. We took therefore a needle that had only a very slight degree of virtue, such as those used in mariners' compasses: and instantly every thing became a magnet in our hands. The crystals of the isle of Elba, those of Dauphiné, of Framont, of Corsica, &c. repelled one of the poles of the small needle by the same point which attracted the opposite pole. We have found few exceptions to this; and perhaps the bodies which are in this state may have lost their magnetism after they were taken from the earth. This we are led to presume from the facility with which they acquire polarity when placed in contact, only for a second or two, with a bar of moderate force.

It is besides possible, that some crystals may have escaped the magnetic action of the globe, by having been so situated that their axis was perpendicular to the direction of the magnetic meridian of their natural place.

608. It occurred to us, that possibly a crystal in the state of a magnet might in consequence of that very state, appear to have no influence on another magnet. To ascertain this, we substituted for the needle the bar that is commonly made use of, and

presented to one of the poles of this bar a crystal of the isle of Elba, by the pole of the same name. The bar possessing scarcely more than the force necessary to destroy the magnetism of the pole that was presented to it, and restore that pole to its natural state, there was neither attraction on that side, nor sensible repulsion on this; while the same pole of the crystal presented to the other pole of the bar, made it move. We thus see, that by confining ourselves to a single observation, we might have drawn a conclusion quite opposite to the truth.

We had still to dissipate a slight degree of uncertainty relative to the results of which we have been speaking. If a piece of iron not magnetised, as a key, for example, be presented in a vertical position, or nearly so, to the austral pole of a needle that is magnetised, that pole is always repelled by the lower end of the key, while the same end attracts the boreal pole *: this, as we have seen (601), is the effect of the magnetism which the action of the terrestrial globe communicates to the key, and which is so fugitive, that if we reverse the position of the key, the contrary effects will immediately take place: but we could not say that the crystals subjected to experiment were in the same circumstances as the key; either because their action was constant, whatever position might be given to them, or that their situation was such, that the inferior extremity repelled the boreal pole of the needle and attracted its austral pole.

609. From these observations it follows, that all pieces of iron, hidden in the earth, or at least most pieces, if they do not abound too much in oxygen, are natural magnets, which only vary in their degree

---

* This experiment is supposed to be made in France, or a like climate.

of force between widely-extended limits: the loadstone, of consequence, ought not to form a distinct species in mineralogy; for the mineral which is called by that name is only the first and most prominent step of a series, where Nature works by shades, and where we may trace her to a very considerable distance, by employing means suited to the delicate gradation of these shades.

610. We shall add a few details here respecting the two metallic substances, that appear to be endued, like iron, with a very sensible degree of magnetic virtue. One is nickel, that, in the state in which nature has hitherto exhibited it to us, is always combined with arsenic or with iron; in which case it produces no motion in the magnetic bar. But this observation proves nothing; for arsenic has this singular property, that its presence, in however small a quantity, entirely conceals the action of magnetism.

Bergmann, who has made numerous experiments on nickel, perceived, that when this metal was refined as perfectly as was practicable, it acted on the magnetic bar. The celebrated Klaproth, also, after discovering that the variety of agate called *chrysoprasium* owed its green colour to the oxydes of nickel, conceived that the portion of this metal which he obtained from that stone might be regarded as perfectly pure *; and observing that the nickel in this state continued to be attractable, he was strongly inclined to the opinion, that it shared with iron the magnetic properties.

We are however tempted to suspect, that nickel, even when deemed pure, still conceals some ferruginous particles, which all the powers of chemistry are unable to extract from it.

We endeavoured, if possible, to remove this suspicion, by subjecting to the test of experiment a thin piece of nickel obtained by Vauquelin, the weight of which was 45 centigrammes, or about 8 grains and ½, and the length 16 millimetres, which are nearly 7 lines. This plate of nickel acted first by attraction on each pole of a magnetic needle; but by following the method of Coulomb (573), polarity was easily given to it, so that it exerted on the needle very distinct attractions and repulsions, and being suspended to a very fine silk thread, it immediately directed itself in the plane of the magnetic meridian. It was observed, besides, that it supported an iron wire that was a third at least of its own weight. Now the quantity of iron that must be supposed to be in the nickel, for it to produce particularly the last-mentioned effect, could not have escaped the very precise methods employed by Vauquelin; which renders it extremely probable that nickel possesses of itself the magnetic properties. To deny this consequence, it must be affirmed, that the small residue of iron so adhering to the nickel that the subtilest analysis cannot separate it, constitutes a magnet of extraordinary force. And though there is nothing in this supposition that implies a contradic-

---

* Annales de Chimie, vol. I. p. 169.

In fact, that other metals, as well as iron, should possess the faculty of retaining the magnetic fluid distributed in their pores, is by no means repugnant to nature; and this kind of prerogative, that was supposed to be granted to iron alone, ought to have been deemed the more singular, since Nature in general is not thus partial in her proceedings.

611. We shall conclude with a reflection naturally arising from our subject. The magnet was long regarded as a source of amusement alone. In the absence of iron it appeared to be nothing; and yet an unexpected discovery has proved, that it is sufficient of itself to render the most important benefits to mankind, and that, under the guise of a simple sport, it concealed a present, destined to be inestimably valuable to navigation. Accordingly, since this discovery, all the resources of philosophic ingenuity have been employed to give to the needles of compasses the form best adapted to augment their energy, and procure them a mobility that should render them more obedient to the action of the terraqueous globe. And we thus see, that an object connected with the sciences, though it seems at first to lead only to idle speculation, ought not on that account to be consigned to oblivion: it affords a species of knowledge calculated to sharpen the sagacity of the mind, and improve its reasoning faculty; a knowledge that often throws new light on common facts and kindred truths, and that partakes of the advantages of these last by enabling us the better to investigate them. Besides, it may in its turn contain some hidden principle that will at last develope itself, and the time we have bestowed upon it may perhaps hasten the moment when it will no longer be unproductive of benefit to society.

VII. LIGHT.

612. HAVING investigated the different phenomena of the fluids diffused around us, and existing in the regions nearest to our globe, we shall now raise our thoughts to the consideration of *light*, which has its source in the stars, and comprehends in its action the whole sphere of the universe.

There is no branch of philosophy more deserving of our study, whether we consider its beauty, or the multitude of phenomena it exhibits. The advantages we derive from the fluid that enlightens us are sufficient of themselves to excite the closest attention, that we may fully understand its properties. If air, serving as the vehicle of speech, enables us to carry on an intercourse of thoughts with our fellow-creatures, how greatly is that intercourse improved by light, which renders their image present to us—their image, which has so many things to say! The eye, more susceptible [illegible] this disadvantage, by faithfully exhibiting our portraiture behind reflecting surfaces, which have the quality of multiplying whatever is presented before them.

Nor are these all the benefits we derive from its properties. Beyond the globes that shine over our heads, there are other luminaries which the eye cannot reach on account of their immense distance, while near us exist a thousand organised beings that equally escape observation from their extreme diminutiveness. Light, by bending itself in transparent bodies terminated by curvilinear forces, has enabled us to perceive these two kinds of infinity, has opened to astronomy a new heaven, and a new field to natural history.

613. There is this advantage in the theory of light, that the course of this fluid is geometrical; so that by a few simple laws, and a precise and rigorous system, results may be obtained without much difficulty. It is well known that the celebrated Saunderson, though blind almost from his birth, delivered public lectures on optics: he considered the rays of light as simple material lines, that acted on the eye by contact; and seeing these lines in his imagination, he succeeded in making others comprehend how their eyes perceived the very objects of which the lines excited in them the impression.

614. Light may be considered in the state of composition that is natural to it, and in which it exhibits a dazzling whiteness; or, as being decomposed into different kinds of rays variously coloured. The properties relating to the first state assist us in determining what may be called *the paths of light.* This fluid always tends to move in a right line. But it frequently happens that some obstacle intervenes, which obstructs its passage, and will only permit it to reflect itself on its surface; or rather some medium or

transparent body, which it penetrates, but experiences in doing so a degree of deviation, to which the name of *refraction* has been given. Though every thing that regards light is comprehended under the general denomination of *optics*, yet this term has been more particularly applied to that branch of the science which treats of direct light: that which considers light as reflected by the surfaces of mirrors was afterwards called *catoptrics;* and that which relates to light refracted in its passage from one medium to another, *dioptrics.* Many philosophers, by obstinately adhering to the order prescribed by this subdivision, have lost sight of a more essential point, that of exhibiting the ideas themselves in the order of analysis, and so as to avoid introducing into the explanation of a phenomenon, circumstances that can only be derived from the sequel. Thus in optics properly so called, they have included many effects of vision that imply a knowledge of the structure of the eye, while that structure cannot be well understood till the principles of dioptrics are known.

The order of analysis to which we have alluded is the one we shall follow here, that we may preserve as

1. *Nature and Propagation of Light.*

615. When a luminous body spreads over all other bodies within its sphere a brightness that affects our eyes, and renders those bodies visible to us, the effect necessarily supposes the existence of a fluid, the action of which is exerted both on the objects enlightened and the organ that perceives them. Is this fluid a subtile matter that fills the whole sphere of the universe, and receives from luminous bodies an agitation that is continued afterwards as the vibrations of a sonorous body are propagated by the intervention of air? This was the opinion of Descartes, and has been admitted by many modern philosophers, who, to adapt it to the phenomena of reflection and the propagation of light, have introduced changes, by supposing that the particles of this fluid, instead of being inflexible and perfectly contiguous, were elastic, with small intervals between them. On the other hand, does light arise from an emission or emanation of the particles of luminous bodies, thrown out incessantly on all sides, in consequence of the continual agitation it experiences? On this hypothesis, which is that of Newton, it would be with light, at least as to the manner in which it is produced, precisely as with corpuscles emanating from odoriferous bodies.

According to Descartes, a ray of light is a string or succession of moleculæ, the motions of which are slight oscillations, that are continually repeated; while according to Newton it is a string of moleculæ that have all an impulsive force, and succeed one another without interruption.

In each hypothesis, the point of every luminous body is considered as the common summit of an infinitude of cones of a very inconsiderable degree of thickness, composed of rays that extend themselves indefinitely, as long as they meet with no interruption. Sometimes these cones themselves are called *rays*, and the axis of the cone is then the line to which we refer the direction of the motion of light.

616. Both hypotheses have very considerable authorities in their favour. Yet, comparing them on all sides, we must give the preference to Newton's. To that of Descartes there is, in the first place, a very strong objection, to which, though it has often been attempted, no satisfactory answer has been given; for, according to this hypothesis, light would not only spread itself in a direct line, but its motion would be transmitted in every direction like that of sound, and would convey the impression of luminous bodies in the regions of space beyond the obstacles that intervene to stop its progress. Accordingly we should have no night; and in total eclipses of the sun, that disappearance of light that changes the brightness of a fine day into complete darkness would never occur.

greater, if we suppose the proportion to be nearly infinite, there would apparently be no obstacle [*] (o).

By a necessary consequence, the quantity of light furnished by the stars, even during an immense period of time, would be so small, that those bodies would experience no sensible diminution.

The partisans of the other hypothesis have not these difficulties to combat, because, on that system, the vibrations of light are like those of air, and we may accordingly apply to them what we have said of the propagation of simultaneous sounds, which cross one another without being confounded: but the advantage it appears to have in this respect is already more than balanced by the objection we have stated; and the facts we shall hereafter exhibit will tend to establish the superiority of the Newtonian hypothesis much more fully. In general, this hypothesis cannot be reproached with leading to consequences that stagger the imagination; and in this respect it resembles a multitude of incontestable truths. And even though it should be considered as not completely demonstrated, it would still deserve to be adopted for this circumstance alone, that it leads to an explanation equally ingenious and satisfactory of various phenomena, and particularly those of refrac-

---

[*] Smith's Treatise on Optics, vol. I. p. 684.

(o) Mr. Brewster very justly remarks, that "all objections of this kind vanish when we attend to the continuation of the impression upon the retina, and to the small number of luminous particles which are on that account necessary for producing constant vision. It appears from the accurate experiments of M. D'Arcy (*Mém. Acad. Par.* 1765, p. 450; *Priestley on Vision*, vol. II. p. 634), that the impression of light upon the retina continues *two minutes and forty seconds*; and as a particle of light would move thirty-two millions of miles during that time, constant vision would be maintained by a succession of luminous particles thirty-two millions of miles distant from each other." Brewster's Ferguson, vol. II. p. 230.—Tr.

-tion and aberration, which, on the hypothesis of Descartes, it is extremely difficult to comprehend.

618. Let us now direct our attention to one of these cones of light which have their summits at different points of a luminous body; and let us conceive a plane, that cuts this cone in a direction, which, for the greater simplicity, we shall suppose to be perpendicular to its axis. If we move this plane in a line parallel to itself, from the summit towards the base, it will intercept circles whose surfaces will regularly increase as the square of the distance from the summit, which is measured by the part of the axis that it intercepts at the same time; and since it always receives the same number of rays, it results that the intensity of light in a given space, taken on this plane, is in the inverse ratio of the square of the distance. Accordingly, if we suppose this plane to be the circle of the pupil of the eye, it will follow that the light received by the eye must be weakened in the same degree, in proportion as it removes from the luminous body.

Let us conceive the eye, placed at first at a certain distance from a torch, to be afterwards withdrawn to a greater distance; the rays that passed by the pupil, in the first case, will be diffused over a space nine times larger, from which we infer that the eye will receive a portion of rays that is nine times less; and consequently if we wish the impression on the eye to be always the same, we must substitute instead of the first torch another, the light of which shall be nine times stronger, that is, shall shed nine times more rays on the same space.

619. An opaque body can never be enlightened but in part by a luminous body; and the space deprived of light, which is situated on the unenlightened side

of the body, is called *shadow*. Shadow, therefore, properly speaking, represents a solid, the form of which depends on that of the luminous body, that of the opaque body, and the position of the two bodies relatively to each other.

620. Let us suppose the two bodies to be the globes *r* and *z* (fig. 82, pl. XII), and that the diameter of the luminous body, *r*, is greater than that of the opaque one, *z*. The shadow will be a cone that may be determined by supposing a right line, *o c*, joining the centres of the two globes, and then drawing a common tangent to the two globes, and extending it till it meets at *a*, the same line produced. If we conceive the tangent, by remaining fixed at the point *a*, where it cuts the line which joins the centres, to revolve about that line, so as always to form the same angle with it, it will evidently describe the surface of a cone that will have for its base the circle of the opaque globe, terminated by all the points of contact; whence we see that the enlightened part of the opaque globe will be greater than the obscure part, the plane which distinguishes them from each other being one of the small circles of that globe, situated in the hemisphere opposite to the luminous body.

621. If the two globes are equal, the shadow will be a cylinder of an indefinite length, and the enlightened part of the opaque globe will be an hemisphere as well as the obscure part.

622. If the opaque globe be larger than the luminous globe, the shadow will become a truncated cone, in like manner of an indefinite length, of which the points of contact with the opaque globe will be on the circumference of one of its small circles, so that the enlightened part of that globe will be less than its obscure part.

623. Shadow, considered on a plane situated be-

hind the opaque body which produces it, is merely the section of this plane in the solid that represents the shadow; from which it follows that, in the case of the two globes which we have cited by way of example, the figure of the shadow on a plane will be a circle, an ellipsis, or some other conic section, according to the positions of the plane relatively to the cone of the shadow formed by the interposition of the opaque body between this plane and the luminous body.

624. When the shadow of a body is projected on a plane, it is not effected by cutting a clear passage through the light which illumines the surrounding parts; but the light itself experiences a sort of degradation, by which its intensity is regularly diminished from the most strongly enlightened points to the space occupied by pure shadow, that is, by shadow properly so called. Let us suppose again, *r* (fig. 83) to be the luminous body, *z* the opaque body, and *u y* a plane situated behind the last-mentioned body: *p x* will represent the projection of pure shadow. Let us now draw the lines *n l*, *q s*, *f h*, &c. tangents to the opaque globe *z*, and that meet the luminous globe, and let us observe merely what passes to the left of the point *p* proceeding towards *u*. The line *f h* being at the greatest possible distance from *p* of all the tangents capable of reaching the globe *r*, it is plain that the point *f*, and for a still stronger reason the more distant points towards *u*, receive as many rays as if the globe did not exist; that is to say, all those proceeding from points between *h* and *d*: but that the point *q* receives none of the rays sent from points between *h* and *s*; that *m* is deprived of all those which originate in points included between *h* and *l*; and lastly, that all the rays emitted from that part of the globe *r* which is turned towards *u y*, are lost as to the point *p*: whence it follows that the effect of the light

decreases progressively from *f* to *p*, which is the limit of the space *p x* occupied by true shadow. To this gradually decreasing light, which extends on one side from *f* to *p*, and on the other from *g* to *x*, the name of *penumbra* has been given. This term is employed by astronomers when treating of the theory of eclipses, and will be used by us in speaking of light decomposed by the intermediation of the prism.

625. The pure shadow of a rod, perpendicularly or obliquely posited on a plane, is a triangle that may be determined by drawing from the top of the rod a line that shall touch the luminous body, forming with the rod the least possible angle. The sides of the triangle will be, first, the part of this line comprehended between the top of the rod and the given plane; next, the rod itself; and lastly, the line drawn from the bottom of the rod till it meets the other line we have mentioned: this last line will be the shadow relatively to the given plane: it will increase and decrease in proportion as the sine of the angle whose summit coincides with the summit of the rod shall be greater or less, that is, in proportion as the luminous body shall sink or rise with respect to the given plane: and if that body move to the right or the left of the position first occupied by the triangle that determines the shadow, the shadow will move on the plane in a contrary direction. It is upon these principles that the science of *gnomonics*, or the art of making dials, is founded *.

---

* By means of the shadow projected on an horizontal ground, we may measure with tolerable accuracy the height of a tower or any other similar object. The method is this: Fix a stick vertically in the ground; measure the part of it that is above the ground; measure also its shadow and the shadow of the tower. The length of the shadows being proportional to the respective height of the two objects producing them, we shall have the height of the tower by multiplying the length of its shadow by the height of the stick, and dividing the produce by the length of the shadow of the stick.

626. The motion of light was for a long time supposed to be instantaneous; but this arose simply from the circumstance of its escaping every method that was employed to ascertain its velocity. Roëmer and Cassini however discovered at last a rule for determining this motion, by observing the eclipses of the first satellite of Jupiter. This planet having a smaller diameter than that of the Sun, the circle that separates its enlightened from its obscure part, is the base of a conic shadow situated towards this last part. The satellites which move round the principal planet, enter and come out of this cone successively, so that their enlightened part becomes itself obscure, and disappears in proportion as they immerge themselves into the cone of the shadow, to appear again afterwards when they emerge from it. Let us suppose the earth to approach its conjunction with Jupiter, that is to say, the term when it would be placed on the same right line between that planet and the sun: there would be, in this case, between the end of the eclipse of the first satellite of Jupiter, and that of the following eclipse, a period of 42½ hours. Let us further conceive that the earth, in moving through half its orbit, has just placed itself in opposition, that is, towards the point where it would be situated behind the sun, relatively to Jupiter. If light had any progressive motion a spectator on our globe would see the first satellite of Jupiter emerge from the shadow after a period equal to as many times 42½ hours as there would be eclipses after the moment of conjunction. But this does not happen, for the spectator sees the termination of the eclipse about 16 minutes later than the calculation supposes; so that in all the intermediate positions, the difference, as far as this limit, has been continually increasing. Now the spectator is at that time at a distance from his first position that

would be measured by the diameter of the terrestrial orbit, the half of which he has traversed, and we know that that diameter is about sixty-six millions of leagues. Hence it has been inferred, that light is 16 minutes in travelling this distance; which is more than four million leagues a minute. Thus, the light that comes to us immediately from the sun does not reach our eyes till the end of eight minutes. It is by combining the progressive motion of light with that of the earth in its orbit, that the aberration of the stars is explained, that is to say, the apparent motion by which the stars deviate from the place where they would naturally be sought for in the heavens. From the velocity of light, as we have stated it, we obtain for the aberration a quantity equal to what observation gives; which verifies at once both the accuracy of the explanation and that of the consequence deduced from the retardation in the eclipses of Jupiter's satellites. In the sequel we shall enquire more minutely into the phenomena of aberration.

627. We shall describe here a meteor which the moderns have called by the name of *aurora borealis*, and shall consider it as a simple phenomenon of light, the cause of which is not yet fully known. In ancient writers we find a number of passages that prove the phenomenon in question to have long been remarked. Every author describes it in his own way; and, according to the appearance in which it presented itself, it has obtained different appellations, such as *lamps*, *flaming torches*, *lances*, &c. It was not till the last century that it began to be studied agreeably to the true principles of philosophy; and no one has shewn more zeal than Mairan in ascertaining the various circumstances attending it, of which the following are the principal [*]. It appears almost always in the north,

---

[*] Traité Physique et Historique de l'Aurore Boréale, p. 115, et seq.

stretching a little towards the west. It begins in general about three or four hours after sun-set. It is preceded by a kind of mist, that exhibits nearly the figure of a segment of a circle, of which the horizon forms the chord. The visible part of its circumference soon becomes fringed with a whitish kind of light, that gives a luminous arch, or a number of concentric arches, distinguishable from one another by edgings composed of the obscure matter of the segment. Rays and streams of light variously coloured shoot afterwards from the arch, or rather from the cloudy segment, in which there is always some luminous breach that seems to afford them a passage. When the phenomenon increases, so as to spread to a considerable extent, its progress shews itself by a general movement and a kind of perturbation in the whole mass. Numerous breaches are formed and instantly disappear in the arch and obscure segment. Vibratory corruscations of light strike, as by shocks, every portion of the matter constituting the phenomenon, and which occupy the visible hemisphere of the heavens. Lastly, when this matter has extended itself as far as it can, there appears in the zenith an inflamed crown, that seems to be the central point as it were in which all the surrounding motions concur. Then it is that the phenomenon exhibits itself in its greatest splendour, not only from the variety of luminous figures that sport in a thousand ways in the upper parts of the atmosphere, but from the beautiful colours with which many of them are adorned. Afterwards the phenomenon diminishes by degrees, yet exhibiting still occasional vibrations and luminous streams. At last the motion ceases; the beams of light which occupied the southern regions and those to the east and west, are compressed and concentrated in the northern part; the obscure segment becomes enlightened, and is then extinguished, sometimes suddenly, and at others with a kind of tardiness, so that it appears in a manner to be dissolved in the twilight of morning, which is the case with the majority of auroræ boreales that are of considerable magnitude.

628. This phenomenon has been attributed to vapours and exhalations, which, in rising from the earth, mix together, afterwards ferment, and at length take fire. Others have supposed that the ice and snow of the polar zone reflected the solar rays towards the concave surface of the upper regions of the atmosphere, whence those rays were sent back to us, and produced the appearances that accompany the aurora borealis. Others again have considered the magnetic fluid as the agent producing this effect, and the resemblance that in some instances had been remarked between appearances of the aurora borealis and the agitations of the magnetic needle (586), seemed to favour this opinion. Among the causes to which the aurora borealis has been ascribed, it was impossible electricity could be forgotten, and the developement of the theory founded on this cause belongs of right to Franklin. According to this celebrated philosopher, the electric fluid conveyed from the equator to the polar regions by clouds that are charged with it, falls with the snow on the ice that covers those regions; and being accumulated there breaks through that low atmosphere, and runs along in the vacuum over the air towards the equator, diverging as the degrees of longitude enlarge, till it finds a passage to the earth in more temperate climates, or is mingled with the upper air, and gives all the appearances we have mentioned. This idea however, it should be observed, is stated by Franklin with diffidence, as a conjecture; and in the paper in which he first mentions the subject, he concludes with words

from which we may infer the nature of his judgment; "this," says he, "is supposed to account for the aurora borealis [*]."

Mairan studied with much care the appearances of the aurora borealis, with the view of supporting, if possible, the particular opinion he had formed of its origin. The principles on which his opinion is founded are these:

Various observations shew, that the sun is surrounded with an atmosphere that is either luminous in itself, or enlightened only by the rays of that luminary; and this atmosphere has been considered as the cause of another phenomenon, known by the name of *zodiacal light*. This light, which is faint and whitish, appears some time after the setting of the sun in the season of spring, and in autumn before it rises [†]. Mairan supposes that the aurora borealis takes place when the matter of the solar atmosphere approaches so near the earth, as to be more exposed to the attraction of this planet than to the sun's attraction. When once within the sphere of activity of the earth, it falls into our atmosphere, and, by the more rapid circular motion of the particles of air in the equatorial regions, is soon repelled towards the poles, where the velocity of rotation is less. This he states as the reason why the aurora borealis appears oftenest in the north; and he endeavours to explain afterwards, by the same principles, the other circumstances belonging to the phenomenon.

As the position of the aurora borealis, which Mairan supposes to have its station in the atmosphere, is sometimes elevated more than 260 leagues above the surface of the earth [‡], this philosopher was obliged to give the atmosphere a height incomparably greater than what is generally ascribed to it. This objection was made to it by the celebrated Euler, who proposed at the same time a new opinion * as to the origin of the aurora borealis, which Mairan in his turn has attempted to refute †. This opinion supposes the particles of our atmosphere to be driven by the impulse of the solar rays to a great distance, and to become luminous by those rays being reflected on their surface. Euler extends this explanation to the appearance of the tails of comets and the zodiacal light, by means of a similar impulse exerting itself, on one hand, upon the atmosphere of comets, and on another, upon that of the sun itself.

---

[*] See his Works lately published by Johnson, vol. I.

[†] Mairan, Traité de l'Aurore Bóreale, p. 12.

[‡] Ibid. p. 62.

From the particulars we have stated it appears that every hypothesis has been tried to account for the aurora borealis. Among the different causes to which it has been attributed, we should be inclined to prefer that of electricity; but as yet this preference has no decisive observation in its favour, and the uncertainty that still accompanies the phenomenon we have been considering, furnishes a new proof, that what we have known longest, is not always that which we know best (*p*).

---

* Recherches Physiques sur la Cause des Queues des Comètes, de la Lumière Boreale, et de la Lumière Zodiacale; Mém. de l'Acad. de Berlin, 1746, vol. II.

† Traité de l'Aurore Boreale, N. 7, p. 341.

(*p*) M. Libes has lately proposed a new theory of the aurora borealis, which has been already adopted by most of the northern philosophers, and may be concisely stated thus: The production of hydrogenous gas is next to nothing at the poles: therefore, so often as the electricity is put into an equilibrated state in the atmosphere, the spark, instead of passing through a mixture of hydrogenous and oxygenous gas, as in our climates, passes through a mixture of oxygenous and azotic gas: it must therefore cause a production of nitrous gas, nitrous acid, and nitric acid, which give birth to ruddy vapours, whose red colour will vary according to the quantity and proportion of those different substances which are generated. These va-

2. *Reflection and Refraction of Light.*

629. We now proceed to consider the changes that light experiences in its rectilinear motion on meeting with bodies that interrupt its passage. When a ray of light, arrived at the surface of a body, returns to-

pours are carried towards the meridian where the air is most dilated, so that they approach more and more towards the spectator; and it is probable their motion may be assisted by a north wind. Sometimes they rise, as if to the zenith of the spectator, and then descend again towards the meridian: and a great number of causes may carry the vapours towards the different points of the heavens, whence originate the different motions taken by the aurora borealis, or its several parts. Lastly, the slight detonations which are sometimes heard, depend upon the small quantity of hydrogenous gas which is found in the upper regions of the atmosphere, and which combines with the oxygen to form water.

These principles at the same time that they account, in M. Libes's estimation, for all the phenomena accompanying the aurora borealis, explain also why it is so common towards the poles, and so rare in the temperate regions; while thunder, which is frequent in the torrid zone, is scarcely ever heard in the polar regions. The disengagement of hydrogenous gas is considerable near the equator, and very little towards the poles: and when we excite the electric spark in a mixture of hydrogen, oxygen, and azote, it combines in preference the bases of the two former gases; the electric spark ought, therefore, to occasion thunder solely in hot countries, and to wards the medium it has traversed, its deviation is called *reflection*. The angle formed by the first direction of a ray with a plane touching that point of the surface where the ray met it, is the *angle of incidence*, and the angle formed by the new direction of the ray with the same plane, is the *angle of reflection*; and observation proves that these two angles are always equal.

630. Hence it follows, that if rays parallel to one another, meet a reflecting surface that is a plane surface, in any angle whatever, they will remain parallel after their reflection.

631. If the rays, instead of being parallel, either converge or diverge, the reflecting surface being still a plane surface, they will retain, after their reflection, the same degree of convergence or of divergence. For example, if the rays are convergent, we may consider the whole of the incident rays as a truncated cone, and the reflected rays as forming the detached part of the cone, which is so placed above the reflecting surface that its base remains confounded with the smallest base of the truncated cone. It is easy to apply the same rule to diverging rays. And thus we see, that, in the reflection on plane surfaces, the rays only change their route, without at all altering their relative position. It is otherwise with reflection on curved surfaces, which alters both the direction and position of the rays in regard to one another.

632. Let us suppose the reflecting surface (fig. 84) to be concave, and to form part of a spherical surface. Let hm, ac, be two incident parallel rays: having drawn the tangents tms, ocy, at the points of incidence, and from the point c, the secant nz parallel to ts, we shall find, that if the incident ray ac, struck upon the secant nz, mg being the reflected ray belonging to the incident ray hm, the line ck, parallel

to *m g*, would be the reflected ray answering to the incident ray *a c*. If we now consider the incidence of the ray *a c* on the tangent *o y*, it is evident that we shall have the angle *k c y* smaller than the angle of incidence *a c o*. Therefore, to give to *c k* the position corresponding with the reflection on *o y*, the angle *k c y* must be augmented, and the reflected ray, as *c b*, will consequently converge with *m g*, and intersect it.

633. Let us suppose that *a c*, while remaining fixed at the extremity *c*, moves from the ray *m h* by its extremity *a*, which will cause the incident rays to converge respectively; the angle of incidence, *a c o*, being augmented, the angle of reflection, *b c y*, must be augmented also: from which it follows that the reflected rays will converge more than the incident rays, since the latter are moved from the parallelism where there was no convergence, while *c b* converged already with *m g*.

If, on the contrary, *a c* were to approach *m h* by its extremity *a*, which would cause the incident rays to diverge, then the angle of incidence, *a c o*, being diminished, the angle of reflection, *b c y*, would be diminished too: whence it follows, that the reflected vergent, or parallel, or even divergent, but always less so than the incident rays.

635. Let us now consider the reflection of the two incident rays, ns, rp, (fig. 85), parallel to each other and to the radius ac of the sphere to which the reflecting surface belongs. Having drawn a second ray, cs, from the point of incidence of the ray ns, we shall have the angle csn equal to the angle csm, these angles being the complements of the angles of incidence and reflection nsy and mst: also, because ns is parallel to ca, the angle csn must be equal to scm; the triangle cms is therefore isosceles, and of consequence ms is equal to cm: and since ms is greater than ma, we shall have cm also greater than ma; accordingly the parallel rays ns, rp, will always be reflected into a point below the upper half, cf, of the radius, ca.

Now, if we suppose the rays ns, rp, to approach the radius of the sphere, the point m, whereto the reflection is made, will also approach the point f; so that when they shall be only at an infinitely small distance from ca, their point of reflection will apparently be confounded with the point f.

636. In another view, if we conceive different incident rays, ns, db, ki, &c. (fig. 86), to be all parallel to the axis and equidistant from one another, the angles of incidence of those which are sensibly remote from the axis, will differ much more from each other, in proportion to their distance, than those of rays nearer the axis, because the inclinations of the small arcs on which the first rays fall go on rapidly increasing, whereas nearer the axis, the arcs deviate but little from the perpendicular direction with respect to the rays corresponding with them. From which it follows, that in a pencil of rays, falling parallel to the radius of the sphere on the curve oag,

all those at a short distance from the axis will meet, after their reflection, in a very narrow space situated nearly in the middle, f, of the radius of the sphere. This narrow space is considered as a point, called *the focus of parallel rays*, whose properties we shall hereafter investigate.

637. If the reflection be on convex surfaces forming part of that of a sphere, all the effects we have mentioned will take place in a contrary way: for, if we prolong behind the concave surface the incident and reflected rays belonging to that surface, we shall have a repetition of the same angles of incidence and reflection, relatively to the convexity of the same surface, on common tangents, with this difference, that the rays which were considered convergent in the first case, will be conceived to diverge in the second, and so reciprocally. For example, if we prolong behind the surface ucx (fig. 87) the rays hm, ac, gm, bc, the incident rays referred to the convexity of the surface will be $h'm$, $a'c$, parallel to each other like the first, and the reflected rays will be mg', cb', which will diverge from each other.

638. The principles therefore of reflection on con-

reflected rays below the convexity, they will unite in a point between the middle of the radius of the sphere and the point where this radius cuts the reflecting surface; and by applying the same mode of reasoning as we adopted with respect to reflection on a concave surface, we shall infer, that in a pencil of rays falling on a convex surface, parallel to one another and to the axis, those nearest this axis will tend to unite in an imaginary focus, situated very near the middle of the radius of the sphere (*q*).

(*q*) The labours of Buffon and Bouguer, on the reflection of light, and on the diminution of intensity occasioned by such reflection, being too important to be entirely omitted, some account of them is given below.

The former of these philosophers receiving the light of the sun in a dark place, and comparing it with the same light of the sun reflected by a mirror, found, that at small distances, as four or five feet, about one half was lost by reflection; as he judged by throwing two reflected beams upon the same place, and comparing them with a beam of direct light; for then the intensity of them both seemed to be the same.

Having received the light at greater distances, as at 100, 200, and 300 feet, he could hardly perceive that it lost any of its intensity by being transmitted through such a space of air.

He afterwards made the same experiments with candles, and always with nearly the same result; and thence concluded, that the quantity of direct light is to that of reflected as 576 to 225; so that the light of five candles reflected from a plane mirror is about equal to that of two candles.

From these experiments it appeared, that more light was lost by reflection of the candles than of the sun; which M. Buffon thought was owing to this circumstance, that the light issuing from the candle diverges, and therefore falls more obliquely upon the mirror than the light of the sun, the rays of which are nearly parallel.

These experiments and observations of M. Buffon are curious; though they fall far short of those of M. Bouguer, both in extent and accuracy. Using a smooth piece of glass one line in thickness, this philosopher found, that when it was placed at an angle of 15 degrees with the incident rays, it reflected 628 parts of 1000 which fell upon it; at the same time that a metallic mirror, which he tried in the same circumstances, reflected only 561 of them. At a less angle of incidence much more was reflected; so that at an angle of three degrees the glass reflected 700 parts, and the metal something less, as in the former case.

Trying the reflection of bodies that were not polished, he found that a

640. When light meets a diaphanous body, that lets it pass into its interior parts, it undergoes another kind of deviation, the laws of which we shall in like manner explain. Any of the bodies which light penetrates bears in general the name of medium. The point where a ray of light enters any medium is called *the point of immersion*, and that at which it comes out, *the point of emergence.* If a ray meets the surface of a medium perpendicularly, it continues its route in that medium; but if the incidence be oblique to the

piece of white plaster, placed at an angle of 75° with the incident rays, reflected $\frac{1}{210}$ part of the light that is received from a candle nine inches from it. White paper, in the same circumstances, reflected in the same proportion; but at the distance of three inches, they both reflected 150 parts of 1000 that were incident.

Of the light reflected from Mercury, $\frac{1}{4}$ at least is lost, and probably no substances reflect more than this. The rays were received at an angle of 11$\frac{1}{2}$ degrees of incidence, that is, measured from the surface of the reflecting body, and not from the perpendicular, which, he says, is what we are always to understand whenever *he* mentions the angle of incidence.

The most striking observations which Bouguer made with respect to this subject, are those which relate to the very great difference in the quantity of light reflected at different angles of incidence. In general, he says, that reflection is stronger at small angles of incidence, and weaker at large ones. The difference is excessive when the rays strike the surface of transparent surface of the medium, the ray turns out of its route, so that it appears broken at the point of emergence: this removal from its path is called *refraction*, and the part of the ray that experiences it is called the *broken* or *refracted ray*. The *angle of incidence* is that which the incident ray makes with a perpendicular drawn from the point of immersion on the surface of the medium, and the *angle of refraction* that which the broken ray makes with the same perpendicular.

641. This being premised, it may happen that light shall pass from a rare medium to a denser medium, or from a dense medium to a more rare medium. In the

---

was even greater than from quicksilver. All things considered, he thought it was not quite so great, though it was very difficult to determine the precise difference between them. In very small angles, he says, that water reflects nearly $\frac{3}{4}$ of the direct light, (649).

There is no person, he says, but has sometimes felt the force of this strong reflection from water, when he has been walking in still weather on the brink of a lake opposite to the sun. In this case, the reflected light is $\frac{1}{3}$, $\frac{1}{2}$, or sometimes a greater proportion of the light that comes directly from the sun, which is an addition to the direct rays of the sun that cannot fail to be very sensible. The direct light of the sun diminishes gradually as it approaches the horizon, while the reflected light at the same time grows stronger: so that there is a certain elevation of the sun, in which the united force of the direct and reflected light will be the greatest possible, and this he says is 12 or 13 degrees.

On the other hand, the light reflected from water at great angles of incidence is extremely small. Bouguer was assured, that, when the light was perpendicular, it reflected no more than the 37th part that quicksilver does in the same circumstances; for it did not appear, from all his observations, that water reflects more than the 60th, or rather the 55th, part of perpendicular light. When the angle of incidence was 50 degrees, the light reflected from the surface of water was about the 32d part of that which mercury reflected; and as the reflection from water increases with the diminution of the angle of incidence, it was twice as strong in proportion at 39 degrees; for it was then the 16th part of the quantity that mercury reflected.

Bouguer likewise paid considerable attention to the subject of light reflected from the planets: with regard to the moon he concludes, that nearly *two-thirds* of the rays that luminary receives are absorbed.—Tr.

first case the refracted ray approaches the perpendicular at the point of immersion, and in the second recedes from it. Also, observation proves, that the sine of the angle of incidence and that of the angle of refraction are always in a constant ratio to each other, when the medium which the light quits and that which it enters remain the same, whatever may be the obliquity of the incident ray. If light pass from air into glass, the sine of incidence will be to the sine of refraction as 3 is to 2; if it pass from air into water, the proportion will be as 4 to 3.

When light is refracted anew at the point of emergence in re-entering the first medium, the same ratio obtains in a contrary sense; that is, if the return be from glass into air, the proportion of the sines will be as 2 to 3, and if from water into air, as 3 to 4; (688).

It follows from this, that if the medium into which the light has first passed be terminated by two parallel surfaces, the light, in quitting this medium, will take a direction that will be itself parallel to that of the incident ray. Several mineral substances have the singular property of soliciting the ray that penetrates them to divide itself into two parts that follow two different routes: this is what is called *double refraction*. In the sequel we shall consider this property, and shall endeavour to illustrate its theory, relative to the mineral bearing the name of *island spar* (a variety of quartz), in which it is more apparent than in other minerals.

642. Let us now consider the effects of refraction in mediums terminated by curved surfaces. Let *d a o p* (fig. 88) be a portion of a spherical surface, and *c a*, *k o*, two incident rays parallel to each other, and to an axis, *y x*, that divides the arch *d a o p* into two equal parts: suppose also the rays *c a*, *k o*, to be equally distant from the axis, in which case they will

meet the surface *d a o p* in the same degree of obliquity: the perpendiculars, *b a*, *h o*, to the points of immersion, are necessarily in the directions of the two radii of the sphere to which the surface we are considering belongs: these perpendiculars then will converge towards each other, and if the medium to which they belong be denser than that in which the incident rays may move, it is obvious that the refracted rays *a i*, *o l*, by approaching the perpendiculars, will also converge towards each other.

643. Let us conceive a second curved surface, *i i l p*, similar to the first, and to be so situated that the two concavities shall be turned towards each other. The rays *a i*, *o l*, in passing into the first medium, will, contrary to the preceding case, remove from the perpendiculars *e i*, *t l*, to the points of emergence; from which it appears, that they will converge still more towards the common point *x* situated on the axis *y x*.

644. Let us suppose that the incident rays *c a*, *k o*, (fig. 89, pl. XIII), being always parallel, meet the surface *d a o p* in different degrees of obliquity, and in such manner, that one shall be between and the other out of the perpendiculars *b a*, *h o*. If the refringent medium be denser than that in which the light moved at first, the bent rays will still converge by approaching the perpendiculars. To prove this, let us conceive that the rays *c a*, *k o*, fall at first on two small surfaces, *d e*, *m p*, (fig. 90), parallel to each other: it is evident that the refracted rays *a f*, *o t*, will be also parallel. Let us now suppose that the small surface *m p* turns round the point of immersion *o*, so as to take the position *n r*, and at the same time that the perpendicular *h o* turns in an equal degree, and takes the position *z u*, while the rays *k o*, *o t*, shall remain fixed: the two little surfaces *d e*, *n r*, may then be considered as forming a part of a curved surface. Now

the angle of incidence *k o h* will be augmented by the quantity *h o z*, and the angle of reflection *s o t* by a quantity equal to *u o s*; and it is evident, that if the sines varied as the angles, the sine of refraction would be too much augmented, for the same proportion to remain. For example, if the proportion were that of 3 to 2, the increase of the angle of refraction ought to be $\frac{2}{3}$ only of that of the angle of incidence, instead of being equal to it. But the sine of refraction is also more increased, in proportion to that of incidence, than in the preceding case; because if two angles be augmented by the same quantity, the sine of the smaller angle will increase in a much greater proportion than that of the larger angle: therefore, for the proportion between the sines to remain the same, the angle *u o t* must diminish, and of consequence the refracted ray *o t* will approach the new perpendicular *o u*, that is to say, will converge towards the other refracted ray, *a f*.

In general, the refraction of parallel rays in a medium that is convex and denser than the medium they have quitted, tends to render the refracted rays convergent: when light passes into a rarer medium, the denser than the one they quit, and which are parallel to the axis, those near this axis must tend to unite beyond the second medium, in a small space that will be their common focus. This focus will equally have place respecting diaphanous bodies terminated on one side by a convex surface, and on the other by a plane surface, as for those which have two sides convex. The position of this focus depends both on the curvature of the medium and its nature; and geometricians have methods of ascertaining that position.

We may also suppose the incident rays to be converging or diverging, and may find, in each case, the respective position which the bent rays ought to take in consequence of the refraction.

We shall reserve the elucidation of those of the various results relative to these suppositions, which we shall need in the sequel, for the several places where they may be introduced with their respective subjects; since it will be easy to deduce them from what has preceded.

647. Hitherto we have considered reflection and refraction as two distinct effects, that take place independently of each other. But observation proves, that the rays which fall on the surface of a refractive medium, different in density from that of the medium in which they were moving, do not all penetrate the second medium; a part being reflected at the contact of the two mediums. Let us suppose the second medium to be rarer than the first: in proportion as the rays, departing from the perpendicular incidence, shall incline more on the surface of the second medium, the number of rays that escape refraction will be more considerable, and there will be a term at which they will all be reflected. This last effect is given immediately by the individual law of refraction; so that we may ascertain, by the ratio between the sines of in-

cidence and refraction, the degree of inclination in which it will take place: for since, in the case in question, the sine of refraction is always greater than that of incidence, it is manifest, that there will be a degree of inclination, where, the angle of incidence being still acute, the angle of refraction will be a right angle, so that the direction of the refracted rays will coincide with the surface of contact of the two mediums; and if we further increase the angle of incidence, that of refraction will become obtuse, and the rays elevate themselves again above the surface of contact. These rays do not then follow the direction of the side of the obtuse angle, agreeably to the law of refraction; but each ray makes its angle of reflection equal to the angle of incidence. We shall presently assign the reason of this.

648. It follows from what we have just said, that, for a given medium, the proportion between the sine of the angle of incidence, where the total reflection begins, and the radius, is the same as that of the sines which measure the refraction in the same medium: for example, when light passes from water into air, the sines being as 3 to 4, the total reflection will be at an angle of incidence of 48° 35′, of which the sine is $\frac{3}{4}$ of the radius.

649. If the second medium, on the contrary, be denser than the first, a part of the rays will in like manner be reflected at the contact of the two mediums; but this part is in general less than in the preceding case, and however oblique the incidence may be, there will be reflected rays, and others that are refracted; in such a manner, however, that the number of the first regularly increases, while that of the second as regularly diminishes, in proportion as the incident rays become more oblique. But this obliquity can never be such that the sine of refraction shall become equal to

the radius, because it is always less than the sine of incidence.

It is in consequence of the portion of rays that thus reflect themselves by escaping refraction, that the surface of a tranquil piece of water, as well as the surface of other transparent bodies, performs, in a certain degree, the office of mirrors, (639 note *q*).

Let us here contemplate the facts we have stated, and examine how far theory has succeeded in ascertaining the causes on which reflection and refraction depend.

650. Philosophers have attempted to explain these, as they have done many other effects, by the ordinary laws of mechanics. They have reasoned in regard to reflection, as if the moleculæ of light had a perfect elasticity, and the surfaces that reflected regularly were themselves perfectly polished. On this supposition, nothing could be more obvious, than the equality of the angles of reflection and incidence, if the moleculæ of light were supposed at the same time to be of a globular form. The force of each globule acting obliquely on the plane of reflection, decomposed itself into two other forces, of which one, perpendicular to the plane, was first destroyed by the resistance of that plane, then completely restored by the effect of the elastic force; the other, parallel to the plane, experienced no alteration, and combining itself with the preceding, produced a new motion in a diagonal line, inclined to the plane in exactly the same degree as the first motion.

651. But these explanations, and others of a similar kind, that reduced every thing here to the ordinary laws of collision, might appear satisfactory, if reflection were considered in an insulated point of view, and a mathematical precision could be attributed to the actions of the producing forces. Newton, accus-

tomed to look at facts in all their bearings, found in their combination in the present instance strong objections to the theory that had hitherto been adopted; and afterwards examining the subject of reflection distinctly, he decided, that the mechanism on which it had been made to depend could not be that of nature.

652. The following are the principal considerations on which his opinion is founded *. When light passes from glass into air, the number of rays that escape refraction, and are reflected at the point of contact of the two mediums, is as great or even greater than when the passage is made from air into glass. This, he states, is saying, in other words, that air is better adapted for reflection than glass, which is by no means probable; and even if it were true, nothing would be gained by it, for if glass be placed in an exhausted receiver, the reflection, in the passage from glass to the vacuum, will be as strong or even stronger than when the air existed.

653. Again, when light passes from glass into air, forming an angle of incidence less than 40 or 41 degrees, a portion of the rays is refracted in penetrating

be placed in contact with water, a considerable portion of the rays will pass through the water, with the same incidence which gave a total reflection when air existed in the room of water. It appears therefore, that reflection and the transmission of rays do not depend on the manner in which they meet the real substance of the glass, but on a certain disposition of the air or water that is contiguous to it.

654. Newton, having stated several other reasons which suppose a knowledge of certain effects we shall ſpeak of hereafter, remarks, that on the supposition of reflection being occasioned by rays striking against the solid particles of bodies, the surfaces of mirrors would not be able to send back the light with the exactness and regularity which is observed by nature. It is not to be presumed that the exertions of art, by means of sand and other analogous materials, should so far succeed in polishing glass, that the minutest particles of that substance should become perfectly smooth, that their surfaces should be exactly plane or spherical, that they should all be turned in the same direction, and compose a single surface varying in no respect through its whole extent. What is called polishing glass, is nothing more than rendering those asperities imperceptible to our eyes which we could before perceive, and substituting smaller asperities in their stead. From which it follows, that if light were reflected by the real substance of glass, it would be dispersed in all directions from surfaces polished with the utmost art, as well as from the roughest. How happens it then that reflection takes place so regularly on the former? There appears to be no other way of getting quit of this difficulty, than by making reflection depend upon a certain force pervading uniformly the whole surface of glass, and exerting its action at

a very small distance. Hereafter we shall mention some observations which prove that bodies really act on rays of light.

655. What we have thus far said of reflection will acquire additional probability from the details we are about to state respecting the theory of refraction. It has in like manner been attempted to ascribe this inflection of light also to the laws of mechanics, by making it depend upon the greater or less resistance of the mediums which it penetrates. But here theory appeared to be at variance with those laws themselves: for it is demonstrable, that a body passing, for example, from air into water in an oblique direction to the surface of that liquid, is refracted by departing from the perpendicular, and that in consequence of the second medium being more resisting than the first. Light, on the contrary, passing from air into water approaches the perpendicular: from which it appears to follow, that dense mediums resist the motion of light in a less degree than those which are rare. As this smaller degree of resistance cannot be attributed to the nature of the medium itself, it has been imagined, that refraction is occasioned by the intervention of a subtile fluid that occupies the pores of the medium, and being purer and more free from every kind of mixture with the grosser fluids, in proportion as the pores are small, becomes thereby less resisting in dense mediums.

Newton explains refraction in a much happier manner, by means of attraction at small distances. His explanation is this:

656. Let *sy* (fig. 91) be a ray of light that penetrates air in a direction oblique to the surface of the medium A B C D, which we shall suppose denser than air. Produce C B until B *r* is equal to the radius of

the sphere of activity of the medium A B C D*, and then having taken on B C, the part Bz equal to Br, let us draw rp and zu parallel to A B. When the ray shall have touched the line rp, it will begin to be more attracted by the medium A C than by the air, and that attraction exerting itself in the direction yn, perpendicular to A B, will combine with the velocity in the direction sy, so that the ray will turn out of its course, describing the diagonal of a small parallelogram formed by the directions of the two forces that solicit it. In proportion as it shall approach A B, it will be more strongly attracted by the medium A C, so that its velocity of approach to this medium will be regularly accelerated, without the horizontal velocity experiencing any change; and its motion at the same time will every instant continue to be inflected; whence it appears, that it will describe a curved line, yt, the concavity of which will be turned towards A B: when the ray shall have arrived below the line A B, it will be attracted at once downwards by the parts of the medium that will be below it, and upwards by the superior parts; and as the attraction of these last extends at first to a distance less than the radius Bz of the sphere of activity of the medium, while the attraction of the lower parts acts through the whole extent of that radius, it follows, that the motion of the ray of light, yt, will continue to accelerate, but by degrees that will regularly decrease, and thus the new portion of the curve tf, that it will describe, will be turned the same way as the first: but as soon as the ray shall touch the line *u z*, it will be wholly immersed in the sphere of activity of the medium, and being then equally attracted on all sides, it will take a rectilinear motion in the direction of the tangent *f k*, to the extremity of the curve *y t f*.

---

* In reality, the action of every molecule of a medium extends indefinitely round that molecule; but as it diminishes so rapidly as to become insensible at a very short distance, it is considered as ending there, and the name of *sphere of activity* is given to the space whose centre coincides with that of the molecule, and whose radius is equal to the distance we have mentioned.

In describing this curve, it is clear, that the ray approaches the perpendicular *c t m*, at the point of immersion; and as the curve is extremely small, the course of the ray appears to be composed only of two right lines, relatively situated like *s y* and *f k*, and which cut each other at the point of immersion.

The same effects are repeated in an inverse order from the point *k*, the distance of which from the line D C is equal to the radius B *z* of the sphere of activity of the medium; so that the ray of light describes here a second curve, *k i e*, similar to the first, but having its concavity turned a contrary way: from which it results, that when the ray is no longer attracted but by the surrounding atmosphere, it moves in a right line, as *e l*, departing from the perpendicular *g i o*, at the point of emergence, in such manner that the angle formed by *e l* and *o i*, is equal to that formed by the

the two curves will not fail to resemble each other; so that, due allowance being made, the motion of the ray may be considered as produced by a single accelerating force, variable within certain limits near the lines A B, C D, and experiencing on both sides the same alterations in a contrary direction *.

---

* We have said (641) that, relatively to any medium, the sine of incidence of that medium is always proportional to the sine of reflection. This, we shall here demonstrate, by means of a principle belonging to the theory of accelerating forces. Let A B be still the surface of the refractive medium, which we suppose denser than the air, *s t* the incident ray, *t i* the refracted ray, *b m* the perpendicular at the point of immersion, and *s b*, *i m*, two other perpendiculars to this same line. If, at the same time, *s t* represent the velocity of the ray in the air, we may decompose this velocity into two directions, *s b* and *b t*, of which the first will represent the horizontal velocity of the incident ray, and the other its vertical velocity. Let us suppose *t i* to be so drawn, that *i m* may be equal to *b s*: the horizontal velocity being always the same while the ray moves according to *t i*, because the action of the accelerating force can occasion no change in that velocity, it will still be represented by *i m* equal to *b s*; whence it follows, that the vertical velocity, relative to the motion according to *t i*, will be represented by *t m*. Now the principle we referred to is this, that the quantity by which the square of the vertical velocity is increased, from the effect of the attractive force of the medium, is a constant quantity, whatever may be the direction of the incident ray: that is, if the square of the velocity *b t* be designated by u^2, and that of the velocity, *t m*, by V^2, the difference $V^2 - u^2$ will be a constant quantity. Let this difference be d^2, and let h be the horizontal velocity *b s*. On *t i*, let us take the part *t z*, equal to *s t*, then through the point *z* draw *z y*, parallel to *i m*; *b s*, or its equal *i m*, will represent the sine of incidence, and *z y* that of refraction. Now, $zy : im :: tz : ti$. But tz, or $ts = \sqrt{(bt)^2 + (bs)^2} = \sqrt{u^2 + h^2}$; $ti = \sqrt{(tm)^2 + (im)^2} = \sqrt{u^2 + d^2 + h^2}$. Therefore the ratio between *t z* and *t i*, or between the sines *z y* and *i m*, is $\sqrt{\frac{u^2 + h^2}{u^2 + d^2 + h^2}}$. But as the incident ray has the same velocity, whatever be its inclination, the numerator $\sqrt{u^2 + h^2}$, or the expression of *t z*, is a constant quantity. Hence the denominator $\sqrt{u^2 + d^2 + h^2}$, being composed of the constant square $u^2 + h^2$ and the constant quantity d^2, will be itself constant; and such, of consequence, will be the proportion between the sines.

Newton

The preceding theory supposes light to be propagated by emission; which affords a more happy illustration of the principle of refraction than can be derived from the hypothesis of pression.

658. As light is transmitted, whatever may be the medium, in all possible directions, we must conceive that it is with the particles of diaphanous bodies, as with those of light itself, that is, that the distances between these particles are incomparably greater than their thickness. Philosophers who admit the propagation of light by pressure, have been led to the same conclusion. Bouguer conceived it possible to elude this difficulty by supposing that the solid parts of diaphanous bodies, which were in the direction of the rays of light, transmitted the action of those rays, by bending or yielding to the subtile matter in the very small spaces where the light was interrupted: but it is not at all likely that these parts should have the form, disposition, and degree of elasticity, that would be required to propagate the vibrations of light with the same accuracy as if the rays of this fluid formed continued lines.

The same theory leads us to a variety of new considerations respecting the causes of reflection and refraction.

659. We have seen (647) that rays which present themselves in a certain oblique direction, on penetrating a medium rarer than the one they have traversed, become all at once reflected at the contact of the two mediums. Now the explanation we have given of refraction will enable us to account for this effect: for the ray of light, arrived within a distance of the con-

---

Newton has given an excellent demonstration of the same result by the method of synthesis. Philos. Natur. Princip. Mathem. vol. I. sect. xiv. prop. 94, theor. 48.

tact of the two mediums, less than the radius of the sphere of activity of the medium it penetrates, and being attracted more by the moleculæ situated above than by those below it, will begin to inflect its motion and to describe a curve which will turn its convexity towards the surface of contact. If the inflection of the curve be such, that the curve cuts the surface of contact, only a part of the rays will be reflected at contact, and the rest will be transmitted. But if the obliquity of the incident ray be so great, that there is an arch of the curve whose tangent is parallel to the surface of contact, the ray, after describing this arch, will elevate itself by describing a second branch of a curve similar to the first, when it will take a uniform motion, in the direction of the tangent to the last arch of the curve; and it is evident that this tangent will be inclined to the surface of contact in the same degree as the incident ray; from which it follows, that the angle of reflection will be equal to the angle of incidence *.

This reflection then is the immediate result of the same cause on which refraction depends, by which it appears to be distinguished from the reflections connected with preceding incidences, and which we might be tempted to regard, on the contrary, as so many instances of exception to the law of refraction: yet it is extremely probable, and indeed this is the opinion of Newton, that reflection and refraction proceed in general from the same power acting differently according to the diversity of circumstances †; for in all the incidences preceding that where refraction is changed into total reflection, the number of reflected rays is also greatest, in general when the

---

* Newton, Philos. Natur. Princip. Mathem. sect. xiv, prop. 96, theor. 50.

† Optice Lucis, book ii. part 3, propos. 2.

obliquity requisite for total refraction is least. Now this is much more the case in proportion as the two mediums differ in density, or, which is the same thing, as the force of refraction, which depends on the magnitude of the angle of refraction, is more considerable; and as, on the other hand, the force of reflection depends on the number of rays reflected, it may truly be said, that in general mediums which refract light most strongly, are those also which most strongly reflect it.

660. Newton, to designate the power we are speaking of, employs sometimes the word attraction, and at other times the word repulsion: for example, when light meets, in a certain degree of obliquity, the last surface of a vitreous mass placed in a vacuum, and is wholly reflected, it is apparent that this effect can only be attributed to the attraction of the glass, the vacuum not being capable of action; but if any liquid, as water or oil, be spread over the surface of the glass, a certain number of rays, that were reflected in the preceding case, will penetrate the liquid, because the attraction of the glass is in part balanced by the contrary attraction of the water or oil*.

to appear, so in the physical effects here adverted to, the repulsive force will immediately succeed to the attractive [*].

Among the rays that move towards the surface of the refringent medium, it will most frequently happen, that some will be repelled and others attracted, to be transmitted afterwards through the medium; and this difference seems to depend on circumstances which Newton has in like manner ascertained, and which we shall state when we come to the article of colours.

661. Newton does not always confine himself to actions at a distance to explain the effects that take place in regard to reflection and refraction. These effects, he presumes, may depend on the influence of a very subtile matter, every-where diffused, even through the interior parts of diaphanous bodies: and conceiving this matter to be denser in rare bodies, and the density regularly to increase, in a small degree, in passing from a dense to a rarer medium, he imagines that on this hypothesis it might be possible to explain how light is refracted in certain circumstances, by gradually inflecting its motion; and how, under other circumstances, it is reflected, by endeavouring to avoid the spaces where the subtile matter is densest, to pass through others where it is rarest [†].

662. To see Newton indulging himself here in such freedom of conjecture, is by no means surprising; for, in his optical questions, he proposes his opinions simply as doubts: they are the history, as it were, of the thoughts which, in his profound meditations on nature, successively occurred to his mind; and they are exhibited to induce other philosophers who may

---

[*] Optice Lucis, book iii, quest. 31.

[†] Ibid. quest. 18.

read his works, to investigate his ideas, and throw additional light upon them.

From the whole of what he has said, it is at least probable that the reflection and refraction of light are produced by particular forces, of the nature of those which act between particle and particle; and that, considering the effects simply as they appear to our senses, we may apply the words *attraction* and *repulsion* to these forces, in the same manner as in chemistry the word *affinity* is employed to denote the tendency which the constituent particles of some bodies have to solicit those of other bodies. This is adding a new class of infinitely varied phenomena to the domain of the forces in question; a domain so vast already, as appears from all we have said, that whatever tends to stretch its limits still farther, must contribute, from that circumstance alone, to the perfection of philosophy, by simplifying the principles and operations of nature. The sort of objection which philosophers long had, and which some still have, to the admission of such forces, arose solely from the desire they felt of discovering, in natural effects, actions analogous to those which we see conprinciples that express general facts, the developement of which gives the clue to every other fact connected with them. There, the philosopher was ignorant of every thing: here, by reasoning from one general fact, which he assumes as a cause, he deduces clear and precise information with respect to all the rest. The occult qualities plunged all the phenomena of nature in a profound and impenetrable obscurity: the forces admitted by Newton, exhibit them in the midst of a space uniformly luminous throughout, except in a single point, where a cloud appears that it has not yet been given to the eye of genius to penetrate.

663. Let us proceed to another effect that has considerable analogy with the preceding ones, and seems to furnish a direct proof of the action of bodies on light at small distances. Grimaldi had observed, that if a ray of light passed through a small aperture into a dark room, the shadows of bodies exposed to that light were larger than they would have been if the rays had just touched the extremities of those bodies.

664. Newton repeated this experiment with a hair, whose shadow was projected on a plane, which he placed successively at different distances from the hair: and he observed, that at a distance of four lines, the size of the shadow was four times that of the hair; that at a distance of two feet, it became ten times larger; and at a distance of ten feet, thirty-five times larger.

As this increase of the shadow had been attributed by many philosophers to the attraction of the atmosphere, Newton, to ascertain if this were the case, moistened the surface of a plate of glass with water, on which he placed the hair, and then put on that plate another similar plate, so that the hair was in the water which occupied the space between the two plates; and he found that the shadow of the hair, at the same distance, was still of the same size *.

This experiment shewed, that the light, when arrived within a short distance of the hair, avoided actually touching it, by bending itself different ways; and this effect could only be ascribed to a sort of repulsion which the hair exerted on the light †.

Newton made a number of other experiments, from which he inferred, that bodies act also by attraction on the rays that pass near them. These seemingly contrary effects are reconciled by the experiments of s'Gravesande, which we shall now describe.

665. Let us conceive *b a c* (fig. 93) to be a section made by a horizontal plane in a sharp blade, like that of a knife or of a sword, situated vertically: if we present the sharp edge, *c*, of this blade to a beam of light, *d m k e*, directed horizontally, the blade will attract the rays *d e*, *f h*, which will be inflected towards it less and less, in proportion as they are the farther removed, so that at a certain distance, which determines the limit of attraction, there will be a ray, *g i*, that will pass without inflection: beyond that limit, attraction will be changed into repulsion, and the ulterior rays,

paratively considerable, as $\frac{1}{10}$ of an inch, neither blade will have any effect on the rays repelled by the other; but every thing will take place respecting each, as in the case of one blade only. There is no need of representing here the repelled rays, which are supposed to coincide with the direct light, op, rs. If the beam were received upon a plane, A B, it would produce a white spot there, on two sides of which the light would expand itself in the form of a kind of fringe, in consequence of the inflection of the rays near the respective blade.

Let the two blades be now brought nearer, by diminishing the space cc'; as long as the rays attracted or repelled by either shall be out of the sphere of action of the other, those which passed nearest the blades, as de, $d'e'$, being intercepted, and the loss not compensated by any increase of force, the white spot will contract itself. If the two blades be brought nearer and nearer, there will be a term where each will repel the rays on which the other acts by attraction, which will increase the inflection of those rays; so that the luminous fringe on each side will approach more and more near to the respective points, A, B, and the intermediate space will be enlarged. At the same time this space will become dark towards the middle, the direct rays which enlightened it there turning off to the right and left, in consequence of the double force that solicited them.

These experiments are very interesting, as we see in them repulsion succeeding to attraction, which becomes evanescent at the point where the rays pass in a direct line, and beyond it negative quantities take the place of positive.

The action of the two forces is not confined to a mere change of the direction of the rays, it decomposes light; so that the fringe exhibits different series of colours, nearly as in coloured rings, which we shall explain in the proper place.

The effect we have here described has been called by many *diffraction of light.* Newton retains the name of *inflection*, and ascribes it to the same general cause that produces reflection and refraction (*r*).

667. We shall conclude this theory of the forces which bodies exert on light, by explaining another kind of result, for which we are again indebted to Newton. This great philosopher undertook to compare the refractive powers of different diaphanous bodies with their densities *. The first he calculates thus: he supposes the light, *c r* (fig. 95), to meet the surface, *a b*, of a body at an almost infinitely small angle, *c r a*; or, which amounts to the same thing, he supposes the angle of incidence, *c r m*, to be apparently a right angle. He then resolves the motion, *r g*, of the refracted ray into two directions, of which one, *r n*, is on the refringent surface, and the other, *g n*, perpendicular to it. As the incident ray, *c r*, had a velocity considered as nothing in the direction of that perpendicular, the whole effect of the motion

which has place in that direction proceeds from the accelerating force, or the refractive power of the medium; and it is demonstrable from the theory of accelerating forces, that if we suppose the line *r n* constant, the refractive power will be as the square of the perpendicular *g n* *: with regard to the density, it is estimated, as we know, from the specific gravity of any body.

668. Newton has found that the refractive powers vary in general according to the respective densities; but that bodies, considered in this view, form as it were two distinct classes;—one, of those which he regards as fixed, such as stones,—the other, of those which he calls fat, sulphureous, and unctuous, as oils, amber, &c. In each class the refractive power is, as we have said, nearly proportional to the density; but bodies of equal density, in the second class, have a much greater refractive power than those of the first class.

669. Now, the great refractive power of the diamond has placed this substance among unctuous and sulphureous bodies; and in the table which Newton has given of the series of ratios between the refractive powers and the densities, the diamond comes after oil of turpentine and amber. (Optice Lucis, book ii, part 3, pr. 10).

---

* We have said (657, note) that the square of the augmentation that takes place relative to the vertical velocity, when the light passes from a rarer to a denser medium, is a constant quantity for all incidences of the ray. Now, the increase which the velocity receives is the effect of the accelerating force, or of the refractive power, which also is always the same in a given medium, whatever be the inclination of the incident ray. If, therefore, we suppose, as in the case stated above, that the incidence forms an infinitely small angle, the square of the increase of velocity will be no longer distinguishable from the square of the velocity itself, that is, it will be represented by $(g n)^2$. Thus, the result in the present case is connected with that which served to demonstrate the law of refraction.

Newton hence concludes, that the diamond is a *coagulated unctuous substance;* an expression, which, in the sense he himself attached to it, is synonymous with *inflammable.*

670. This great philosopher goes farther. He remarks, that water has a mean refractive power between those of the two classes of bodies, and that it partakes probably of the nature of both; for it contributes to the growth of plants and of animals, which are composed at once of sulphureous, fat, and inflammable materials, and of earthy, dry, and alkalised ones.

Thus Newton read, as it were, in the results of refraction, that the diamond was a combustible body; and that water contained an inflammable principle. In announcing these notions he expresses himself in the chemical language of the times; and on this account we cannot but wonder the more, how, placed at so great a distance, and proceeding in a path so apparently devious, his genius was able to approach so near to important truths, which the state of human knowledge at that period would seem to have rendered inaccessible (*s*).

Decomposed Light, or Colours.

671. The rays which luminous bodies transmit immediately to our eyes, bring us the image of those bodies, accompanied with that vivid clearness, which we sometimes express by the very word *light*. Such of these rays as are reflected by bodies capable of repelling them, announce, in like manner, the presence of those bodies, by exhibiting their portraiture, but under a particular appearance which we express by the word *colours*. Philosophers have hence concluded, that reflection did not merely transmit to us the rays in the same state in which they are received by the reflecting surface, but that this surface has a fitness to modify the action of the rays, and thence to make us perceive the images of bodies clothed and decorated

---

bonic acid; a result which agrees remarkably with the proportion of the component parts stated in note (*q*), par. 243, vol. I. The application of the rule is found to hold not only in simple mixtures, but in more intimate combinations, provided no very considerable condensation has been produced. Thus ammoniacal gas produces the effect indicated by the quantities of azote and of hydrogen which enter into its composition; but if the condensation be too great, there is some alteration though very small. Such is the case with water.

The examination of muriatic acid gas, made after these principles, shews that its radical cannot be azote; and also that it cannot be an oxyde of hydrogen, containing less oxygen than water.

The refraction of the diamond (3·2119 according to Newton, that of air being 1) being much stronger than that which is indicated for carbon by the refractions of carbonic acid, alcohol, ether, and other substances of which carbon makes a part; M. Biot concludes, that the diamond cannot be pure carbon, and that we must admit at least one-fourth of hydrogen to satisfy the results of the experiment. See *Biblioth. Brit.* vol. XXXII, or *Philos. Magazine*, vol. XXVI. pp. 152, 292.

For an ingenious paper by Dr. W. H. Wollaston, describing a simple, yet elegant, method of examining refractive and dispersive powers by prismatic reflection, the reader may consult *Phil. Trans.* 1802, or *Phil. Journal*, vol. II. N. S.—Tr.

in their colours. But in what does this kind of modification consist, whether we consider it as being in the rays themselves, or in the objects that determine it? Of what nature is this power, whose inexhaustible fecundity gives birth to those diversified tints, that distinguish the surfaces of different bodies, and admit of such delicate gradations of shades, often united and as it were melted together in the coloration of a single body? The solution of these important questions we owe to the discoveries of Newton.

Consideration of Colours in Light.

While light was regarded as homogeneal, and its rays as indifferent in themselves respecting this or that colour, the difference of colours was attributed to the different motions which the particles of bodies gave to rays reflected from their surface, or refracted within them. Some philosophers, assimilating colours to sounds, made them consist in the greater or less frequency of the vibrations of the subtile matter that served them as a vehicle.

and where we admire throughout a happy choice of decisive experiments, the art of placing them in the order in which they elucidate each other, and that correctness of reasoning which, in the inferences he draws, exhibits a faithful translation of the language of facts.

673. Before we proceed to the results of the experiments in question, it may not be amiss to give some general notions of the form and effects of the prism by which they are made. This instrument is straight and triangular. It is commonly made of white glass that is as free as possible from bubbles, veins, and other similar defects. Its lateral faces should be perfectly plane, and of a fine polish. The angle formed by the two faces, one receiving the ray of light that is refracted in the instrument, and the other affording it an issue on its returning into the air, is called the *refracting or refringent angle* of the prism.

674. We have seen (641) that a ray of light, penetrating a medium terminated by two parallel faces, assumes, on repassing into the air, a direction parallel to the direction it had before it entered the medium. This is not the case when the medium is a prism whose faces are inclined to each other: for the emergent ray necessarily makes an angle with the incident ray. We must however except the case where the incident ray, and the perpendicular at the point of incidence, are in a plane whose section, with the face on which the ray falls, is parallel to the edge that passes through the summit of the refringent angle. For if we prolong this plane till it meets the face through which the ray issues, its section with that face will be parallel to the first section; and as the ray remains on this plane, it follows that it is in the same case here as if the two faces were parallel to each other, and accordingly it will come out of the prism in a direction parallel to its first direction.

675. Let us now suppose that *a b c* (fig. 96, pl. XIV) represents an infinitely thin plate or a section of a prism on a plane perpendicular to the axis; that *b* is the point appertaining to the refringent angle, and *h g* the incident ray. If we turn the prism about its axis, while the ray *h g* remains fixed, and if the motion of this prism be such, that it causes the emergent ray *n m* to sink more and more below its first position, there will be a limit beyond which the extremity *m*, which had hitherto descended, will begin to rise. This limit will obtain when the emergent ray *n m* shall make, with the perpendicular *o r*, an angle, *m n r*, equal to the angle *h g s*, formed by the incident ray *h g*, with the perpendicular *p s*: whence it follows, that the angles *a n m*, *c g h*, which the two rays will form with the corresponding faces of the prism, will be in like manner equal. If the point *b* be turned upwards, the motions of the ray *n m* will be directly the reverse of what we have stated.

The position that gives the equality between the angles *a n m*, *c g h*, ought, therefore, to be regarded as the limit of all the other positions. Now we know that when a quantity, by varying, proceeds towards a

It results from this, that in the positions of the prism approaching that where the refractions of the rays $m\,n$, $g\,h$, are equal on both sides, the ray $m\,n$ remains nearly parallel to itself, so that its extremity m is for an instant almost stationary. These different notions we shall find of use to us in the sequel.

676. Let us now proceed to the experiments by means of which Newton established his theory. These experiments are of two kinds. The first, which are the most important, refer to the consideration of colours in light; the second relate to circumstances that determine bodies to reflect the different colours under which they present themselves to our eyes.

To give to the first kind of experiments all the extent of which they are susceptible, Newton has examined light in three different states, by investigating in succession that which comes from coloured bodies, that which the sun immediately transmits to us, and lastly, that which is reflected from polished surfaces.

---

the text: but it by no means applies universally with respect to geometrical quantities; as may be shewn by a very simple example. Let us contemplate the changes of the variable ordinate intercepted between the axis A X, and the circle $M\,m\,m'''\,n$ (fig. T. pl. XIII). This ordinate, if considered with regard to the superior branch of the curve $M\,m\,m'$, &c. will have a minimum value in the position P M, a maximum in the position $p'\,m'$, and a minimum again in the position $p'''\,m'''$. But, considered in relation to the inferior moiety of the curve, P M will be a maximum, $p'\,n'$ a minimum, and $p'''\,m'''$ a maximum again. The points M, m', m''', and n', therefore, determine the limits of the variations in the ordinate. Yet, it is manifest that, while these variations are very slow when the ordinate approaches the points m', n'; they are very rapid when the ordinate comes near the other limiting points M, m''': and the mutations are in a kind of medium state with regard to increase and decrease, when the ordinate has attained either of the intermediate positions $p\,n\,m$, $p''\,n''\,m''$. The rapid variations about the limits P M, $p'''\,m'''$, would be still more striking if the curve were an ellipse whose minor axis was equal to $M\,m'''$: but the obvious instance of the circle will suffice to shew that the observation of our ingenious author is not to be admitted universally.—Tr.

677. He took a piece of thick paper, of a rectangular form, and of a very black ground. Having divided the rectangle into halves, by a line parallel to its shorter sides, he tinged one half with a red, and the other with a blue colour. They were both deep colours, and of considerable intensity. The paper was placed before a window *, in such a manner that the longer sides of the rectangle were parallel to the horizon, and the bisecting line perpendicular to the plane of the window: moreover, the angle formed by the light that came from the window to the plane of the paper, was equal to that which the same plane formed with the rays reflected towards the eye. Things being thus disposed, Newton looked at the paper through a prism, whose refracting angle was about 60°, and whose axis was also parallel to the horizon; and the result of his observation was as follows: When the refringent angle of the prism was turned upwards, in which case the refraction raised the image of the paper above its first position, the blue half appeared more elevated than that which was red. The refringent angle being turned downwards, the reverse was the case, that is, the position of the blue was lower than that of the red. From this first experiment Newton concludes, that the rays which came from the blue half were more refrangible than those which came from the red: for it was evident, the longer sides of the paper being parallel to the edges of the prism, that the rays of the two colours, which proceeded from the subdivision of these sides and

---

* For the experiment to succeed, the paper must be at a moderate distance from the window, as about 25 centimetres (9 or 10 inches), and opposite the supporting wall underneath the window, to temper the effect of the light, which would exhibit on the paper all the different colours of which we shall presently speak, and thereby eclipse the colours painted upon the paper.

those of all the intermediate lines, were, relatively to the prism, in precisely the same circumstances; so that if they had undergone equal refractions, all the points of the image which answered to each of the longer sides of the paper and each of the intermediate lines must have appeared at the same height *.

Newton then wrapped a very black silk thread several times about the same paper in such a manner that the threads appeared like so many lines drawn upon it. He placed the paper in a vertical position against a wall, one of the colours being to the right, and the other to the left. Choosing the period of night for the experiment, he put before the paper, at a very short distance, a lighted candle, the flame of which corresponded with the junction of the two colours, while the apex of the flame was as little as possible above the lower edge of the paper. Lastly, he erected on the floor, opposite the paper and at the distance of about six feet, a lens of 4¼ inches broad, which so collected the rays proceeding from the different points of the paper, that their points of concourse, behind the lens, were situated at the same distance of about six feet; and the result was, that the image of the coloured paper was painted on another paper posited in the place of these points of concourse, as the images of external objects are delineated in the interior of a dark room, or on the bottom of an artificial *camera obscura*.

By moving the second paper, sometimes towards the lens, and sometimes from it, Newton endeavoured to ascertain the distance where the image of each coloured half of the fixed paper had most distinctness, and he judged it to be where the images of the threads drawn over the paper were themselves distinctly terminated. Now, at the distance where the red was perfectly distinct, the blue had so confused an appearance, that the lines which crossed it were scarcely perceptible; and, on the other hand, where the blue exhibited itself in all its clearness, there was a very imperfect image both of the red and the lines to which it served as a ground. This second distance was about an inch and half nearer the lens, than that which gave a distinct vision of the red; and as the incidence of the rays on the lens was the same in both cases, it followed that the blue rays were more refracted than the red, so as to converge sooner.

---

* Optice Lucis, book i, part 1, propos. 1, theor. 1.

It is not essential to the success of the experiments, that the apparatus should be arranged precisely as we have stated. For instance, in the first experiment we shall equally succeed by inclining the prism and the paper towards the horizon. But in the positions adopted by Newton the phenomenon is more marked and perspicuous; and in general he has reduced all his experiments to that kind of fixed terms, where, by being conducted with more care and precision, they afford clearer results. He does not, however, affirm that all the light proceeding from the blue part of fraction through the prism, might project on the wall of the room opposite the window the coloured image, known by the name of the *solar spectrum*. The axis of the prism was perpendicular to the direction of the ray, and by turning the prism slowly round this axis, Newton saw the spectrum descend and ascend alternately on the wall. Between the descent and ascent there was an instant when the spectrum appeared stationary; and from what has been said above, we may judge the direction of the prism to have been such at that instant, that the refractions of the incident rays and those of the emergent rays were on both sides equal. Newton fixed the prism in this position, and adopted it in general for all his experiments *.

679. The image of the sun, depicted on the wall opposite to the window, was an oblong figure, the lateral bounds of which were two tolerably distinct parallel right lines, and the upper and lower extremities two semicircles confusedly and indistinctly terminated, the colours decaying there and gradually vanishing. The breadth of the image was in proportion to the apparent size of the sun's diameter, for it was 2⅛ inches including the penumbra, and was besides 18½ feet from the prism. Now by subducting from this breadth the diameter of the hole in the window-shutter, which was a quarter of an inch, and by measuring the angle, which, having its summit towards the prism, was subtended by the breadth thus reduced, this angle was found to be about ½ a degree, which is the measure of the sun's apparent diameter.

To understand this, let us suppose figure 97 to represent, in an horizontal projection, every thing relating to the phenomenon: that *st* is the sun's diameter; *on* the diameter of the aperture in the window-shutter; *s n z*, *t o r*, two rays which, issuing from the extremities of the sun's diameter, proceed, after intersecting in *y*, to pass by the extremities of the hole; *s o h*, *t n e*, two other rays going directly towards the same extremities, so as not to cross till they arrive at *l*, on the other side; and lastly, that *r z* is the line at which these different rays terminate on the walls: the penumbra will be measured by the lines *e r*, *h z*.

---

* Optice Lucis, book i, part 1, propos. 2, theor. 2.

Now let *a b c d* be the projection of the prism; this projection will be a rectangle, because of the horizontal position of the prism. In another view, it is obvious that the refracted rays and the emergent rays will remain in this same plane, and that besides they will issue from the prism in directions parallel to their first directions: and as the incident rays meet the prism almost perpendicularly, on account of the minuteness of the angle which they make with each other, we may suppose, without sensible error, the emergent rays to remain on the prolonged directions of the incident rays.

Now Newton, having taken off from the breadth, *r z*, of the image, the part *g r*, equal to *o n*, found that the angle *g n z*, which is apparently equal to the angle *r y z** or the angle *s y t*, was about half a degree. With the image considered lengthwise, it was very different; it was about 10¼ inches in this direction, and the refringent angle of the prism employed in the experiment was about sixty-four degrees. With a prism having a less refringent angle, the length of the image was diminished, but the breadth remained the same.

By causing the prism to turn upon its axis, in such manner that the emergent rays should become more oblique to the face of the prism through which they issued, he observed the image to increase about two inches, or rather more, in the direction of its length.

---

* It is a consequence of this that *g n* is parallel to *r o*.

But when he gave a contrary motion to the prism, which augmented the obliquity of the incident rays with regard to the face of the prism through which they entered, he observed that the image became contracted by an inch or two, and always in the direction of its height.

680. Now, according to the received laws of optics of that period, the length of the image, when it was become stationary, ought to be equal to its breadth, that is, the image ought to be circular: for let *a c b* (fig. 98) be a vertical section of the prism; *r f*, *x m*, two incident rays that proceed from the extremities of the sun's diameter, taken also vertically, and which cross before they pass through the hole in the window-shutter: further, let *m h*, *f i*, be the refracted rays; *h p*, *i n*, the emergent rays; and *p u* the length of the image, delineated on the wall.

We have said (675) that when the image becomes stationary, the refractions are on both sides equal. This limit relates to the point, *t*, situated nearly in the middle of the image, and answering to the ray *y r s t*, whose refraction is a mean between those of all the other rays above and below; so that it is the emergent ray *s t* that is inclined to *a c*, in the same degree as the incident ray *y r* is inclined to *b c*; and the image is considered as stationary when, during the contrary movements of the prism, the point *t* ceases to ascend or descend.

But, on the hypothesis of all the rays being equally refrangible, the refraction at *m* would be equal to that at *i*, and the refraction at *f* equal to that at *h* *; from which it follows, that the inclination of the emergent rays hp, iu, one over the other, would be the same as that of the incident rays ym, gf, that is, about ½ a degree; and as the slight deviation which the rays mh, fi, would experience in the interior of the prism might be neglected, because the incident rays are nearly parallel, it results that, on the same hypothesis, the length of the image ought to be equal to the breadth, or in other words, the image ought to appear circular. Therefore, since it is five times longer than it is broad, the rays ym, yf, and the intermediate ones, must be differently refrangible; and those which form the upper part, p, of the image (fig. 98), more so than those which form the lower part, u.

---

* The angle of incidence, *y m q*, of the ray *y m*, is rather less than the angle of incidence, *y r z*, of the mean ray *y r*; because the perpendiculars *z q*, *z x*, are parallel to each other, and *r y* converges towards *m y*. Hence

681. Now, such was the distribution of the colours of the image, that its most refrangible extremity, p, exhibited violet, while the opposite extremity, u, the refraction of which was the least, presented red, and the parts between, reckoning from the red, were successively orange, yellow, green, blue, and indigo.

If the prism were removed to a certain distance from the aperture in the window-shutter, and the hole were looked at through the prism, disposed as in the preceding experiment, there was seen in like manner an oblong and coloured image, in which the most refrangible colour was violet, and the least refrangible red; and the intermediate colours, counting from the

also the angle of refraction, $hm\iota$, is less than srx; therefore, mh diverges a little with respect to rs; mhd is greater than rsk, and phe greater than tsl. By a similar train of reasoning we may prove, that $yf\gamma$ is greater than yrz, and ifr greater than srx: whence it follows, that fi diverges also with respect to rs. Therefore, fin is smaller than rsk, and uio, than tsl. Consequently, each of the angles ymq, and uio, is less than either of the equal angles yrz, and tsl; and each of the angles $yf\gamma$, and phe, is greater than either of the angles yrz, and tsl. Now in the case of the limit, and supposing the rays equally refrangible, the decrements are equal, as well as the increments. Hence, $ymq = uio$, and $yf\gamma = phe$.

violet, were the same, indigo, blue, green, yellow, and orange.

682. It followed from these experiments, that, *cæteris paribus*, the rays differ remarkably from one another by their degrees of refrangibility. But whence did this difference arise? Was it the effect of a constant and uniform law differently modifying the refraction of different rays? Was it to be regarded as accidental? Or, lastly, Was the opinion of Grimaldi to be adopted, according to whom each ray dilated and spread itself like a fan? These were questions still undecided, and to find their solution it was necessary to have recourse to new experiments.

Newton judged, that if the lengthening of the image were occupied by the dilatation of each individual ray, or any other deviation of a like kind, the image, when refracted anew in the lateral direction, would extend over a breadth equal to its length. To prove the effect of this second refraction, leaving the apparatus arranged as in the preceding experiment, he placed a second prism behind the first, but in such a manner that the axis of one crossed that of the other at right angles, and the light refracted upwards by the first, was afterwards refracted sideways by the second; and he remarked, that the image retained the same breadth; the only difference was, that its position was a little oblique with respect to the first.

683. This result had brought things to the point where nothing remained but to draw the inferences which the developement presented as it were of itself to the genius of Newton. Let us endeavour to follow here the course of his ideas. The stream of light entering by the hole in the window-shutter, is composed of rays which, by their nature, have different degrees of refrangibility. This stream, received immediately on the wall, without any intervening prism, forms on

it a luminous circle, in which the extremities of all the rays are every-where united and mixed with one another. Place to meet the light a prism with its axis parallel to the horizon, the effect of the horizontal refraction being to make the rays issue in directions parallel to their first directions; whatever be their degree of refrangibility, there will result no sensible separation of the rays in that direction. But the rays situated in one and the same vertical plane striking, in different inclinations, the two faces of the prism that form the refringent angle, will separate from one another by the effect of refraction. The most refrangible of all, if they existed alone, would form on the opposite wall a circular image, or nearly so. The least refrangible, if they too existed alone, would exhibit themselves in a circular aspect, the position of which would apparently be a little lower than that of the first. Imagine between these two circles an infinite number of other circles, projected by rays whose refrangibilities form a series of intermediate degrees between those of the two extreme circles, and conceive further, that all these different circles fall at once upon the wall: their centres will be found on the circle they will project on the wall will have its new position a little to the right or left of the preceding, and the more so as this circle shall be produced by rays that have a greater degree of refrangibility. Let us suppose, that in consequence of the position of the second prism, the deviation of each circle should be from right to left; and let us conceive a vertical line traced on the wall and passing through the centres of the different circles, of which the image proceeding from the horizontal prism alone was composed: the centre of the circle produced by the most refrangible rays will be the most remote from this vertical line, by virtue of the refraction of the second prism; the circle that will have deviated the least will be that belonging to the least refrangible rays, and all the intermediate circles will be more or less distant from the vertical, to the left, according as the rays which produce these circles shall be more or less refrangible: whence it follows, that the different centres will be formed on an oblique line. We may conceive also, that the length of the image will be rather increased, since it is included between the same horizontal lines as before, but is placed obliquely with regard to them.

Newton having placed a third, and even a fourth, prism, behind the second, to multiply the lateral refractions, always obtained the same result, without any sensible increase of the image as to its breadth.

New experiments, the detail of which would lead us too far, are brought in aid of the preceding ones: and what strength does truth derive from their combination, when there is not one that, considered in itself, does not appear superior to the others!

685. It remains for us to speak of those which have reflected light for their object; and we have here again proof heaped upon proof. Newton having

taken a triangular prism, the refringent angle of which was 90°, and each of the other two 45°, received a solar ray on one of the faces that formed the refringent angle, the position of the prism being such that the emergent rays issued through the base, which was turned towards the horizon. Now, from what we have said before (647), a portion of the rays which met this base was reflected at its interior surface, and came out at the other face of the refringent angle, while the part that escaped refraction, on passing again into the air, became refracted. The reflected rays fell on a second prism, and, after being refracted in crossing it, formed a coloured image on a sheet of paper placed at a proper distance *.

In proportion as Newton turned the first prism on its axis, the different colours of the image increased successively in intensity, beginning with the violet and ending with the red; and the following were the consequences resulting from this gradation.

The rays which heightened each colour produced this effect merely by escaping from the refraction that took place on the issue of light from the first prism, and then mingling with the reflected rays that passed to the second prism; and the tone of a colour was at its greatest height, at the moment when the refraction of the rays belonging to that colour was changed into total reflection (647) †. Hence we see, that the light reflected on the interior base of the prism, united to itself, one after another, the additional rays relating to the different colours, proceeding from violet to red, that is, beginning with the most refrangible rays, and

---

* Optice Lucis, book i, part 1, exper. 9.

† It is evident that the inclination of the prism, requisite for the total reflection of the rays of each colour, varied according to the diversity of colours, so that to each degree of inclination there was a corresponding *maximum* of intensity relative to a particular colour.

ending with those which were least refrangible. Accordingly, in this experiment, the reflected light became gradually composed of rays variously refrangible. Now this light differed in no respect from that of the incident rays which came directly from the sun, for reflection is simply a deviation of light, which does not alter its nature. The experiment in question served, therefore, to confirm, in some sort, by the way of synthesis, that which the preceding had established by a contrary operation which may be compared to analysis.

The same experiment shewed, that the rays which were most refrangible, were also the most disposed to reflect themselves, and that the least refrangible were those that had the least tendency to reflection.

The results we have mentioned, lead to new considerations, that will enable us still more completely to fathom this important subject.

686. When we speak in philosophy of *red* rays, *blue* rays, *violet* rays, &c. we are far from supposing that the rays are really coloured; such language expresses nothing else than a certain disposition of the rays to produce in us the different sensations which we designate by the terms *red, blue, violet,* &c. The experiments we have related merely prove that there exists in a beam of light coming to us directly from the sun, a certain portion of homogeneal rays adapted to produce in us the impression of *violet,* and which we therefore call *violet* rays for the sake of conciseness; another portion of rays, in like manner homogeneal, we call *blue* rays; and so through the whole: and these experiments teach us further, that the *violet* rays, *blue* rays, *green* rays, &c. have different degrees of refrangibility, from the violet, which are the most refrangible, to the red, which are less so than any of the others.

But here, as in many other natural phenomena, the law of continuity takes place (note to par. 183), that is to say, the refraction goes on diminishing, by imperceptible differences, from the violet to the red; and thus the cone of light which crosses the prism, is resolved there into an infinite number of cones, whose axes form with each other very small angles, and hence it is that the bases in a great measure cover one another in the coloured image formed by their aggregate. The colour of the rays varies also by shades from cone to cone in such manner that the shade may be referred to seven principal kinds of colours, which are violet, indigo, blue, green, yellow, orange, and red. Newton expresses himself on this point in the clearest terms *; though, judging from the explanation which philosophers in general have given of his theory, it would seem as if he admitted in light but seven perfectly decided colours, succeeding each other abruptly, without transition or shade.

687. The mixture of all these shades, some of which encroach upon others, in the coloured image produced by refraction, renders this image, therefore, an ex-

To accomplish this object, at least in a considerable degree, a small hole is made in a window-shutter, and at the distance of about twelve feet from the aperture, a lenticular glass is placed, and beyond the glass a sheet of white paper, at such a distance that the light refracted by the lens might represent distinctly on the paper the image of the hole made in the window-shutter: now the effect of this lens is to contract greatly the image in question. Lastly, there is placed behind the lens, at a short distance, a prism that projects, either upwards or on one side, the coloured image of the sun. Then the different circles which constitute this image being themselves considerably diminished in size, separate from one another, and the more so as the breadth of the image is small in proportion to its length. Newton succeeded in rendering the image seventy-two times longer than it is broad; so that each of the colours of that image might be considered as nearly approaching to simplicity and homogeneity *.

In reality, the colours in this state can no more be sensibly changed by any refraction. For example, if the coloured image be received on a sheet of black paper with a small circular orifice in it of about four millimetres, or two lines in diameter, and if, having caused the portion of the image transmitted by this hole to pass through a second prism, we make it fall perpendicularly on another sheet of white paper, no difference is observable between its length and breadth, but it appears to be of an exact circular form; which proves, that all the rays that compose it are refracted regularly, and in the same degree.

688. Here a new subject of enquiry presented itself, that of comparing the laws of the particular refrac-

---

* Optice Lucis, book i, part 1, propos. 4, prob. 1, exper. 11.

tions, which the different colours of the image underwent, either with one another, or with the general law of refraction. When philosophers were assured from experiment, that the sine of incidence was in a constant ratio to that of refraction (641), they thought that all the rays of light were refracted by the same quantity, under the same incidence; but the truth is, that the rays are unequally refrangible, and the results obtained by these philosophers must be regarded as a kind of middle terms between all the refractions of different rays; so that we can only conclude from these results, that the green rays which answer to the middle of the coloured image of the sun, being separated from the rest, should have their angle of refraction constantly in proportion to their angle of incidence. Newton has made direct experiments which prove that the ratio is in like manner constant for the rays of all the colours; and this may strictly be demonstrated geometrically, from the supposition, infinitely probable, that the action of bodies on light exerts itself perpendicularly to the surface of those bodies; for, on this hypothesis, we may apply to any kind of rays the general demonstration we gave when speak-which he was assisted by a friend whose eye was well disciplined in distinguishing colours, he marked on the coloured image the limits of the seven principal colours, by drawing the diameters of the two extreme circles, of which one gave violet, and the other red, and then dividing the intermediate space into seven parts, by lines parallel to those diameters: lastly, having extended one of the rectilinear sides of the image beyond the red, till the prolongation was equal to the distance between the diameters of the two extreme circles, he measured the distance between each transversal line, and the extremity of the prolonged line, beginning with the diameter of the violet circle, and proceeding successively from violet till he came to red, which made in all eight distances. Now he found that these distances were to each other, as the numbers 1, $\frac{8}{9}$, $\frac{5}{6}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{9}{16}$, $\frac{1}{2}$; and the series of these numbers had this singular property, that it was similar to that which represents the intervals of sounds, *ut*, *re*, *mi-bemol*, *fa*, *sol*, *la*, *si*, *ut*, of which our musical scale is formed, taken in the minor mood *.

It results from what has been said, that the division of the line on which Newton marked the limits of the seven principal colours, was the same as in a monochord, the different lengths of which gave the seven sounds of the gamut belonging to the minor mood. This conformity of proportions has led some philosophers to suppose, that there was a real analogy between sounds and colours; but it is here rather an accidental analogy, and there are stubborn reasons besides, which will not yield to the pretension of making colours sing (*u*).

---

* Optice Lucis, book i, part 2, propos. 3, prob. 1, exper. 7. The sixth relation $\frac{9}{16}$ differs a little from the relation $\frac{8}{15}$ which answers to it in our gamut (359); it gives for *si* a sound rather lower than that which we have assigned.

Newton had previously ascertained, by means of another experiment, the ratio between the sine of refraction of the least refrangible rays of the solar spectrum, and that of the most refrangible rays, under the same incidence. If we denote the sine of incidence by 50, we shall have 77 for the sine of refraction of the red rays, and 78 for that of the violet rays.

Now in the division of the coloured image which gave the limits of the adjoining colours, the positions of the transversal lines, which answered to those limits, were determined by the points of the wall on which the extremities of the refracted rays relative to the same limits fell; and from the minuteness of the angles which these rays formed with one another, one might take, without sensible error, the distances between the points of the wall where they terminated, or, which amounts to the same thing, the distances between the limits traced on the image, for the successive differences between the sines of the angles of refraction, in passing from the glass into the air; accordingly, by dividing the difference between the numbers 77 and 78 into parts proportional to the intervals between the limits of the colours of the image, there would be 77, $77\frac{1}{8}$, $77\frac{1}{5}$, $77\frac{1}{3}$, $77\frac{1}{2}$, $77\frac{2}{3}$, $77\frac{7}{9}$, 78, to express the sines of refraction of the different rays relative to one and the same sine of incidence expressed by 50. Hence it resulted, that the sines of refraction of the red rays relative to all the shades of that colour, extended from 77 to $77\frac{1}{8}$, those of the orange rays from $77\frac{1}{8}$ to $77\frac{1}{5}$, those of the yellow rays from $77\frac{1}{5}$ to $77\frac{1}{3}$, and so on, for the green, the blue, the indigo, and the violet rays.

690. There are therefore in light, rays of an infinite number of shades different in colour, of which each is subjected in its refraction to a proportion between the sines which is, as it were, inherent in it, and experiences no alteration. These rays, which differ both in their tints and their degrees of refraction, ought to be considered as heterogeneous, since when they meet all at once, under one and the same incidence, the surface of one and the same refringent medium, they experience on the part of that medium different attractions, which imply a diversity in their modes of being. The mixture of all the colours forms the light which we call *white;* so that it is merely necessary to suppress in this light some of the colours which compose it to produce a particular colour, which will vary according to the number and kind of those which are permitted to remain. Thus, if we receive on a lens the differently coloured rays which diverge on coming out of the prism, and place a sheet of white paper beyond this lens, where the rays which it has rendered convergent unite in a common focus, the luminous circle which they form on the paper will be a white colour. Things being thus arranged, if we place between the lens and the prism an opaque body, that intercepts

one or more of the colours refracted by the prism, the white light received by the paper will instantly give place to a colour, either simple or mixed; for example, if the violet, the blue, and the green, be intercepted, the other colours, that is, the yellow, the orange, and the red, will form a compound colour, which will be a fine yellow: suppress on the contrary the last three colours, and you will have a mixture of violet, green, and blue, which will border on the colour of green. In all these variations the rays do not change their quality, nor do they act on one another, they merely mix together in different proportions.

691. These consequences were confirmed by a new experiment of Newton's, the idea of which he derived from a well-known observation. It consists in this: The impression of light on the retina is not an instantaneous effect, and hence it is, that if you make a burning coal turn rapidly in the air, the eye will see a circle of fire that will appear fixed during the motion; for in that case the impression made from the first instant on a determined point of the organ, by the light issuing from the coal, continues till the ray returns to the place where it was when the impression was made, and thus the sensation is renewed continually, without having been destroyed. From this observation, Newton proposed to try if the different colours of a solar spectrum might not act on the eye by succeeding one another so rapidly, that at the instant of each impression, the traces of preceding impressions being not yet effaced, the result might not be the same as that of a single sensation produced by a permanent white colour *.

To verify this idea, Newton provided himself with an instrument which had the form of a comb with

---

* Optice Lucis, book i, part 2, prop. 5, exper. 10.

sixteen teeth, about forty millimetres, or an inch and a half broad, and the intervals between tooth and tooth each of about fifty-four millimetres or two inches. Having caused the rays which had passed through a prism to fall on a lens, he disposed a sheet of paper beyond the lens at such a distance that the sun's image appeared white there, when the rays passed freely from the prism to the lens. He then placed in succession the teeth of the comb immediately before the lens so as to intercept a part of the coloured rays which were on the point of entering it, while the other rays, which were permitted to pass through it freely, painted on the paper the circular image of the sun. This image then lost its whiteness, and constantly assumed a colour composed of all those of the rays which had not been intercepted, and this colour varied continually with the position of the comb. But when Newton gave so rapid a motion to the comb that the quickness with which the impressions of the different colours succeeded each other, no longer gave the eye time to distinguish them, he saw neither red, nor yellow, nor green, nor blue, nor violet; but the confused mixture of all the colours occasioned the sensation of a uniform whiteness, of which, however, no part was white, every colour still preserving its existence there apart. Now, when afterwards he withdrew the comb, there was no alteration in the mode of existence of the white light which the eye still perceived on the paper; only all the colours in this case acted at once on the organ, whereas, when the comb was employed they acted in succession, but with such very small intervals of time, that they were equivalent in effect to a concourse of simultaneous actions.

692. In the coloured image produced by the refraction of the prism, the orange was situated between the yellow and the red, and the green between the

blue and the yellow. Now we know that by artificially mixing yellow with red we obtain an orange colour, and a green colour by mixing yellow with blue. This fact has led some philosophers to suppose, that orange and green, produced by the refraction of light through the prism, proceeded from the mixture of the three neighbouring colours, and ought to be suppressed in the order of homogeneal colours. But this idea is manifestly contradicted by experiment: for if you keep apart the green rays of the image, by intercepting the other colours, and cause these rays to pass through a second, a third, or a fourth prism, they will constantly retain their green colour. On the contrary, if you intercept the green, red, and violet, rays, and leave the yellow and blue only mixed together in the focus of a lens, by the process which we have before described (687), they will constantly preserve their green colour; but cause this colour to pass through another prism, and it will instantly resolve itself into its component colours, so that the blue and the green will be painted separately on a sheet of paper placed beyond the second prism. It is unfortunate for the opinion in question, that the red should be so remote from the violet, which is situated by the side of the blue; for violet is artificially formed by a mixture of red and blue; and we may accordingly compose in painting a sort of imitation of the coloured image exhibited in the experiment, by merely employing three colours, red, yellow, and blue: and indeed history teaches us, that the ancient painters wrought for a long time with these colours only *. This faculty, of doing much with little, may possibly be a source of wealth to the art, but it would be rendering Nature truly poor,

---

* Encyclop. Méthod. part 1; Beaux Arts, vol. I, page 160.

to confine her operations to the narrow limits of our artificial methods.

We shall proceed now to the consideration of certain phenomena produced by the separation of the different colours of which direct light is the assemblage.

693. Let us suppose that we see through a prism, *a b c*, (fig. 96, pl. XIV), a neighbouring object, such as a sheet of white paper of a certain size, situated vertically, and of a rectangular form, having two of its borders parallel to the axis of the prism. The position and figure we have mentioned are chosen merely to reduce the experiment to a simple case; and what we shall say respecting it, may be applied, with due allowance, to all the other cases.

From what we have said (678) of the refraction of rays through a prism that turns on its axis, we may conceive, that, according to the different motions given to the prism, the image of the paper will be seen in the position where it becomes stationary, or rising above that position, or sinking below it. Now in each of these positions the upper border will present successively, and in a descending order, four bands of different colours, of which the most elevated will be pure red, and the three others mixtures of red and orange, of orange and yellow, and of these three colours combined with green. The lower border will exhibit four other bands which, taken in an ascending order, will give pure violet, then violet mixed with indigo, then those two colours united to blue, and finally, the last three colours united to green, and the intermediate space will be white.

To explain this effect, we shall observe, that from all the different points of the paper there proceed rays of every colour, which, after being refracted by crossing the prism, are directed towards the eye in the form of a sort of pyramid, whose summit is in the pupil. Let us suppose there existed red rays only: the whole surface of the paper would appear tinged with red; and each of the other kind of rays, if it existed alone, would give to the surface of the paper in like manner its own tint. Now let us unite all the colours, and we may consider the images which they tend to produce, each separately, as so many rectangles of seven different colours which encroach a certain degree one on the other by their upper or lower borders, owing to the difference of the refractions. Now in this encroachment, as it were, of one colour upon another, the red will be raised a little above the orange, the orange above the yellow, and so through the series, in such a manner that towards the opposite border the violet will sink below the indigo, the indigo below the blue, &c.

Hence it results, that the upper part of the paper will be terminated by a band of pure red, that below this band there will be a second mixed with red and orange, then a third of red, orange, and yellow, and a fourth of red, orange, yellow, and green. If we take the colours afterwards in an ascending order, we may conceive that the lower part must be bordered with a band of pure violet, above which will be another mixed with violet and indigo, then a third of violet, indigo, and blue, and lastly a fourth, of violet, indigo, blue, and green. In the space between this fourth band, and that answering to it among the upper bands, all the colours being mixed will produce white.

We suppose here, as we have said above, the paper to have a certain extent; the less considerable its height, the more distinct will be the colours from one another, and the nearer will they approach to the arrangement that takes place in the coloured image produced by prismatic refraction, by means of the ordinary experiment: so that the height may be so inconsiderable as just to permit the different colours to succeed one another without any white interval.

The Rainbow.

694. Light, which embellishes with so much magnificence a pure and serene sky, by means of the innumerable stars that are spread over it, sometimes, in a dark and cloudy sky, exhibits an ornament, that, by the pomp, splendour, and variety of its colours, seems to attract the attention of every eye that has an opportunity of beholding it. In this short description the reader will easily recognise the rainbow. We know that this phenomenon never takes place but when a cloud opposed to the sun dissolves in rain; from which it follows, that to observe this spectacle the back of the spectator must be turned towards the sun. Frequently there are two bows; an inner one, in which the colours are more vivid, and an outer one, in which they are paler; each exhibits the same series of colours as the image produced by the prism, that is, red, orange, yellow, green, blue, indigo, and violet; but red is the uppermost colour in the interior bow, and violet in the exterior bow. Both the bows depend upon the refraction of light combined with its reflection; and they are never seen but when the incident rays form with the emergent rays a certain angle, which we shall presently specify.

695. Antonio de Dominis appears to have been the first who attempted, with any degree of success, to explain the rainbow philosophically. He imitated this phenomenon by means of an experiment which we shall state, and determined the different inflections of light in the drops of rain; but he is not accurate in

this point, with respect to the exterior bow. Descartes improved his statement, and gave in general more precision to the mode of tracing the progress of the rays. And lastly, Newton taking up the subject, added the degree of perfection that was wanting, by analysing the distribution of the colouring, which is the soul, as it were, of the phenomenon. It is upon Newton's principles that we shall found our explanation.

696. Let *f z p q* (fig. 100) be the circumference of a great circle formed by a section made in a transparent globe of a density greater than that of the air. Having drawn any diameter, as *f p*, let us suppose that a beam, *y f*, of incident homogeneal rays, situated first in the direction *f p*, rises parallel to itself along the quarter of the circle *f z*: this beam, being arrived, for example, at *a b*, will be refracted at the point of incidence, in a direction such as *b d*, and will then be subdivided into two parts, of which one will repass into the air, and will there be refracted again, while the other will escape refraction, by reflecting itself from the interior concavity of the circle, in such a direction, *d t*, that the arch *d q t* will be equal to the

double the arch dp[*]. Now in proportion as ab ascends along fhz, dp itself goes on increasing as far as a certain limit, beyond which it diminishes. This will appear by considering, that the angle of incidence always increasing in proportion as yf rises, if we take two incident rays, as eh, ab, the refracted ray, hr, which belongs to the first, will necessarily incline towards bd, which is the refracted ray relative to the second. Now as long as the part of the quadrant, fhz, which the incident rays meet, is a little inclined to the diameter fp, the ray hr is entirely above the ray bd, even supposing the arch bh extremely small: but in proportion as the arch becomes more oblique, the ray hr inclines more towards bd; so that there is a term where the extremities of the refracted rays coincide in a common point; and beyond that term the two refracted rays, such as hd, su, (fig. 101, pl. XV), which belong to the incident rays, eh, us, cross each other; whence we see that dp (fig. 100, pl. XIV) goes on increasing as far as the term where the points r, d, become contiguous, and afterwards diminish from that same term, to which the *maximum* of the angle axm answers[†].

697. Let us call to mind here the observation we made before (675), that the variations of a quantity when it approaches its limit, or only begins to deviate

---

[*] Having drawn xl to pass through the centre, and consequently to cut into two equal parts the arch bt, we shall have for the measure of axm, $\frac{1}{2}(bt-go)=bf+fl-dg=gp+dp-dg=dg+dp+dp-dg=2dp$.

[†] The more oblique is the part of the arch which the incident rays meet, the more the difference between the incidences at the two extremities of one and the same arch, bh, hs, &c. (fig. 101, pl. XV) increases, these arches being supposed equal. Besides, it is manifest that the rays eh, us, are nearer to each other than the rays ab, eh. Now these two causes tend to increase the respective inclination of the two refracted rays; and such is this increase at last, that the rays cross each other.

from it, are nearly insensible. Now we conclude from this, that in the vicinity of the point *d*, where the degrees of increase by which the refracted rays incline over each other are almost infinitely small, the density both of the refracted and reflected light at the concavity of the circle is much greater than any-where else; whence it follows, that the convergent rays proceeding from that same light, such as *t m*, *i k*, &c. (fig. 101), will be themselves more abundant in a small given space.

On the other hand, all the emergent rays will be apparently parallel to one another, because the refracted rays meet in one and the same point. If, therefore, we suppose that refracted rays fall at the same time on all the points of the quadrant *f h z*, and that the eye of a spectator is situated at the point *o*, on a line passing between *m t* and *k i*, that eye will receive many more rays than it would do if it were situated any-where else; partly because those which are in the direction of the eye are accumulated in greater abundance, and also because, being parallel, more of them will enter the pupil, than if the eye were only in the way of those which issue, diverging, from other points included between *f* and *q*.

To those rays which accumulate in a manner in the vicinity of the limit the name of *effectual* or *efficacious rays* has been given, from their being the only ones which make a very sensible impression. They may be likened to those which a concave mirror or a lens collects in a common focus, where their force is concentrated.

698. The rays which are reflected from the point *d* to the point *t*, do not all repass into the air; some of them are reflected a second time at the concavity of the circle, so that the light undergoes in succession two, three, four, &c. reflections, at each of which

there are a certain number of rays that return into the surrounding atmosphere.

699. Let us then suppose that a beam of light, hp (fig. 102), undergoes in the interior of the circle two reflections, by which a portion of the refracted rays moving in the direction pf, is sent from f to o, then from o to n, and returns into the air in the direction mn, which, at the point z, crosses the incident ray hp; the angle mzh, or nzp, will also have a limit, which, in the present case, will be a *maximum;* and it will be at this limit, when, taking a second incident ray near to the first, and which will of consequence undergo in like manner two reflections, one from g to d, the other from d to b, we shall have of parallel to dg; from which it follows, that the emergent ray ba, will also be parallel to the emergent ray mn; and by applying here what we have said (697) of rays that experience but a single reflection, we shall understand that an eye placed in the direction of a line drawn between mn, and ba, will receive many more rays than in any other position, as it will be in the direct path of the efficacious rays.

700. Now if we suppose the incident light to pass from air into water, the *maximum* of the angle axm (fig. 100, pl. XIV) will obtain for the red rays, when that angle shall be 42° 2′; and for the violet rays, when it shall be 40° 17′. In the same case, the arch bf which measures the angle of incidence of the ray ab, since ab and fp are parallel, is 59° 24′ (x).

(x) As the analytical calculus from which these angles is deduced is comparatively simple, it may be given in this note. The principles on which it depends are as follow: 1. The effective rays which emerge after one reflection, have their angle of incidence so ordered, that its nascent increment or smallest increase is double the contemporary increase of the angle of refraction: for the nascent increment of the angle of incidence is at the centre, while that of the angle of refraction is at the periphery, and both insist upon the same arch, On the other part, the *minimum* of the angle *m z h* (fig. 102, pl. XV), relative to the red rays, is 50° 57′, and relative to the violet rays, 54° 7′; the angle of incidence of the ray *h p* being then 71° 54′.

701. Let us now conceive a spectator whose eye is placed at O (fig. 103, pl. XVI), and four globules of water, *d f*, *a c*, *k r*, *g l*, so situated, that the solar rays S *d*, S *a*, S *r*, S *l*, after two refractions and one reflection in the lower globules, form with the emergent

---

2. The tangents of the angles of incidence and refraction of the efficacious rays, are to each other as 2 to 1 when they emerge after one reflection: for, in two angles whose sines are in a given ratio, their contempory increments are as the tangents of those angles.

3. Hence, in the present case where the mediums through which the ray passes are water and air, we have merely to find those angles whose sines are as 4 to 3, and their tangents as 2 to 1.

Geometrical solutions of the General Problem of which this is a particular instance, may be seen at pa. 343, *Simpson's Algebra*, and pa. 118, *Simpson's Select Exercises*. But the case before us may be solved algebraically thus:

Let cos. I, cos. R, be the cosines of incidence and refraction respectively; then the squares of their sines will be $1-\cos.^2 I$, and $1-\cos.^2 R$, radius being unity; and the squares of their tangents will be $\frac{1-\cos.^2 I}{\cos.^2 I}$, and rays angles equal to those we have cited, that is, O *x* S, 40° 17′; O *z* S, 42° 2′; O *y* S, 50° 57′; and O *u* S, 54° 7′: we suppose here the rays to come from the centre of the sun; and as the distance they transverse is nearly infinite compared with that which separates the globules of water, they are deemed parallel to one another.

Now it is clear from what we have said before (700), that the angle O *z* S of 42° 2′ being that which the red incident and emergent rays make with each other, in the case where those rays are most condensed, the eye will perceive the red to be the most vivid in the globule *a c*, as well as in all the others situated in like manner in the direction O *c*. Moreover, the angle O *x* S being that which relates to the efficacious violet rays, the observer will see the violet most intense in the globule *d f*, and in all those situated in the direction O *f*; he will also see only red in the first globules,

This transformed into an equation, gives $9-4\cos.^2 R = 16-16\cos.^2 R$: whence, we have $\cos.^2 R = \frac{7}{12}$, and $\cos. R = \sqrt{\frac{7}{12}} = \frac{1}{6}\sqrt{21} =$ cos. 40° 12′ 11″. Consequently, 40° 12′ 11″ is the angle of refraction: and the angle of incidence, being that whose sine is to the sine of 40° 12′ 11″ as 4 to 3, is = 59° 23′ 28″. Hence, half the angle contained between the incident and emergent rays, or half the semi-diameter of the bow, is 2 (40° 12′ 11″)—59° 23′ 28″ = 21° 0′ 54″. The double of this is 42° 1′ 48″ or nearly 4z° 2′, for the apparent semi-diameter of the greatest bow formed by the red rays.

In the same manner, the apparent semi-diameter of the greatest rainbow formed by the violet rays, is found to be about 40° 17′: and this subtracted from 42° 2′ leaves 1° 45′ for the apparent breadth of the bow, supposing the rays emanated from the centre of the sun only. But the sun's apparent diameter is about 32′; which being added to 1° 45′, gives 2° 17′ for the apparent breadth of the bow, conformably to observation.

After a nearly similar method it may be shewn that the cosine of incidence of the effective rays, which emerge after any number, *n*, of reflections, is to radius, as $\sqrt{\sin.^2 I - \sin.^2 R}$ to $\sqrt{(n+1)^2 - \sin.^2 R}$. And from this, the dimensions of the secondary, and succeeding rainbows, may be deduced.—Tr.

and violet only in the second: for the orange rays, for example, whose refraction is greater than that of the red rays, to be effectual, ought to be so refracted that the angle, formed by the incident with the emergent rays, shall be less than $42^\circ\ 2'$ and greater than $40^\circ\ 17'$; and since the angle in question is the greatest of all those which the same rays form, it cannot take place with respect to the globule *a c*, or the globule *d f*, but will exist in some one of the intermediate globules. It follows from this, that the colours comprised between the red and the violet, as well as the shades of those colours, will be seen alternately in the globules situated between *a c* and *d f*, in the order prescribed by their different degrees of refrangibility; so that the succession of all the colours, taken in the descending order, will be thus: red, orange, yellow, green, blue, indigo, and violet; but the violet being mixed with the whitish colour of the adjacent clouds, will thereby be weakened, and will border on purple.

702. Now let O P be a right line parallel to the solar rays, and what is called the axis of vision. Let us conceive the rays O *x*, O *z*, and all those belonging

terior bow, we shall conceive that the angle O *u* S of 54° 7′ being that which the incident and emergent violet rays when acting most efficaciously make with one another, the observer will perceive the violet deepest in the globule *g l*. Also the angle O *y* S of 50° 57′ performing the same function with respect to the red rays, the observer will perceive the red most vivid in the globule *k r*. The other colours will exhibit themselves successively with all their shades in the intermediate globules, and will extend, as well as the violet and red, over the surface of a curvilinear band, A B *r* H N *g*, which will form the exterior bow. But all these colours will be presented in a reverse order to those of the interior bow; so that from the top to the bottom their arrangement will be thus: violet, indigo, blue, green, yellow, orange, red. They will also be much fainter, because the rays which produce them undergo two reflections, on each of which there are always some that pass into the air.

704. The apparent breadth of the interior bow, according to the same principles, is 1° 45′, the difference between the angles O *x* S and O *z* S; that of the exterior bow is 3° 10′, the difference between the angles O *y* S and O *u* S; and the distance of one bow from the other is 8° 55′, the difference between the angles O *y* S and O *z* S.

705. Such in reality would be the dimensions of the two bows if the sun were merely a point, or the drops of rain received no other rays than what came from its centre; but they equally receive those which flow from all points of its disk, which increases a little the breadth of each bow.

To comprehend the manner in which this augmentation takes place, let us observe that the sun's diameter, seen at the immense distance at which we are stationed from this luminary, subtends an angle of about 30 minutes (679). Now, if we confine our attention to the two rays which emanate from the extremities of the diameter taken vertically, we shall easily perceive, that the effect of the upper ray is the same, respecting that of the central ray, as if the sun, after producing the two bows by means of this ray alone, were all at once raised a quarter of a degree above the horizon; and to have in like manner the effect of the lower ray, we have only to suppose that the sun sinks a quarter of a degree towards the horizon.

This premised, let $s' s''$ (fig. 104, pl. XV) be the vertical diameter of the sun, and $s z$ be the ray which gives the red of the interior bow, as we have just explained; let o be still the position of the eye, $o z$ the emergent ray, and $o p$ the axis of vision. Let us conceive the point s transferred to s', so that the arch $s s'$ shall be 15′; that the incident and emergent rays relative to the point s' may make still with one another the angle $s' z' o$ of 42° 2′, we must suppose the incident ray $s' z'$, instead of being wholly above the ray $s z$, as is seen in fig. 105, to cross it in some point, g (fig. 104), of the atmosphere. In like manner the lower ray $s'' z''$ should cross the ray $s z$; from which it follows, that it will present to the eye the red in the globule of water $a'' c''$, placed above the globule $a c$, which gives this colour by virtue of the refraction of the central ray $s z$; and that the upper ray will exhibit the same colour in the globule $a' c'$ situated below the globule $a c$ *.

Now the angles $z'' g z$, $z g z'$, (fig. 104), being each 15′, the angles $z'' o z$, $z o z'$ will be of the same value. But the ray $o z'$ being included in the angle which subtends the breadth of the interior bow produced by

---

* Let us conceive the circumference of a circle to pass through the points g, z, o; it will also pass through the points z', z'', on the hypothesis of the equal angles $g z'' o$, $g z o$, $g z' o$, so that the small arc $z' z''$ will apparently coincide with the breadth of the rainbow.

the rays that flow from the centre *s*, there will thence be no increase in the direction of that breadth; but the ray *o z''* being elevated above the ray *o z*, will augment, on this side, the angle that subtended the breadth, by a quantity equal to 15′. By employing the same mode of reasoning to the violet colour, we may infer that the refraction of the upper ray ought also to increase the breadth of the bow by a quantity equal to 15′, which should be added below: from which it follows, that the total breadth will be greater by 30′ than that which took place from the single refraction of the central ray, and will thus be 2° 15′. (See note *x*, par. 700).

By a necessary consequence, the breadth of the exterior bow will receive the same augmentations, and will be altogether 3° 40′; and the distance between the two bows being diminished by 30′ will be only 8° 25′. Newton has verified these dimensions by direct observations *.

706. We see a greater or less part of the rainbow, according as the sun is more or less elevated above the horizon. When this luminary is near the plane of the horizon, the axis O P (fig. 103, pl. XVI) of vision, which is at the same time that of the cone formed by all the effectual rays, coincides also with the horizon, and the rainbow in this case appears in the form of a semicircle. In proportion as the sun is elevated, the axis O P sinks in the same degree below its first position, and the bow regularly diminishes. Lastly, when the sun is 42° above the horizon, the axis being sunk the same number of degrees below this circle, the summit of the rainbow touches the horizon: whence it follows, that if the sun were higher, the interior bow would disappear, and there would only

---

* Opticæ Lucis, book i. part 2, propos. 9, prob. 4.

remain a portion of the exterior bow, which would not disappear till the elevation of the sun should be 54°.

707. If we are on an eminence when the sun is at the horizon, or even below it, the axis O P will be elevated above that horizon, and thus the bow will exceed a semicircle; and if the cloud, instead of being very high, is at a short distance from the observer, it may happen that the eye will perceive the whole circle [*].

708. We have said (698) that the rays which enter each drop of rain undergo continual reflections, by virtue of which they describe a kind of polygon that returns back upon itself; but at every contact of the rays with the concavity of the globule, some escape reflection by passing into the air, so that the number of those which continue to be reflected from point to point is always diminishing. We may therefore suppose incident rays so situated relatively to the bow they meet, that after three reflections, those of a deter-

---

[*] Smith's Treatise of Optics, p. 587, edition of 1767.

mined colour which shall return into the air being in the state of effectual rays (697), shall direct themselves towards the eye; and thus a third rainbow, more elevated than the second, will be formed: but the colours in this case are so much weakened by the loss they sustained at each of the three reflections, that it is seldom this third rainbow can be distinguished, unless the part of the sky fronting the spectator happens to be very dark, and the sun shines strongly on the opposite part *. In the same manner we may conceive the possibility of a fourth rainbow, formed by rays that undergo four reflections and two refractions, and so of a greater number; but these bows can only be perceived by the eye of theory.

Sometimes there are also seen under the primary rainbow, other bows that seldom present all the colours belonging to this phenomenon, one or two only in general being visible. Pemberton ascribes these secondary bows to rays that disperse themselves, but at the same time at so trifling a distance from those which produce the ordinary rainbow, that the eye is in their direction. Of the colours that proceed from these rays, some are lost in the violet part of the first bow, and others are seen distinctly in the space below †.

The experiment by which Antonio de Dominis represented the phenomenon of the rainbow consisted in suspending a glass globe filled with water in a situation in which it was exposed to the sun, and moving it up and down in such a manner that the angles formed by the incident and emergent rays varied from 42° to about 51°. And in this globe the colours were observed to paint themselves successively in the

---

* Musschenbroek, Essai de Phys. vol. II, p. 793.

† Pemberton's Elements of Newton's Philosophy.

order in which they present themselves in the globules of rain.

710. From the explanation we have given of the rainbow, it is easy to account for several effects, which are so many copies, as it were, of this magnificent picture. We succeed in the artificial imitation of it, by throwing water into the air, so as to scatter it, turning our back to the sun. We often perceive its colours at the summit of a *jet d'eau;* sometimes it is painted on the grass when wet with dew, and sometimes it mixes its tints with the flowers that embellish the fields.

Consideration of Colours in Objects.

711. We have learnt, from Newton's theory, of what colours considered in light consist, and we have found the cause of the various impressions which what is called *red, yellow, green,* &c. produces on our eyes, in the different qualities inherent in the rays, and indicated by the different degrees of refrangibility of which they are susceptible. We have now to con-

blue, or green rays, and extinguish all the other kinds.

712. A great number of bodies are fitted to reflect at once several kinds of rays, and of consequence they appear under mixed colours. It may even happen, that of two bodies, which should be green, for example, one may reflect the pure green of light, and the other the mixture of yellow and blue. This quality of selection as it were in bodies, which varies to infinity, occasions the different kinds of rays to unite in every possible manner and every possible proportion; and hence the inexhaustible variety of shades which nature, as in sport, has diffused over the surface of different bodies.

713. When a body absorbs nearly all the light which reaches it, that body appears black: it transmits to the eye so few reflected rays, that it is scarcely perceptible in itself, and its presence and form make no impression upon us, unless as it interrupts, in a manner, the brightness of the surrounding space.

But for a body to reflect one kind of ray rather than any other kind, there must be something in that body which determines the preference. In what then does a red body differ in this respect from a yellow, a green, or a violet one? Various attempts have been made, and on various hypotheses, to resolve this question. Newton, who entered upon the subject with great earnestness, has been here again equally successful in interrogating nature, by a series of admirable experiments, of which we shall give the results *.

714. Having taken two object-glasses of a telescope, the one plano-convex, the other a little convex on both sides, he placed one of the faces of this upon

---

* Optice Lucis, book ii, part 1, observ. 4, 5, 6, &c.

the plane face of the former, and pressed the two glasses at first gently, and then by degrees more closely, against one another. The effect of this gradual pressure was an appearance in the plate of air between the glasses of different coloured circles, which had the point of contact for the common centre, and which increased in number according to the greater degree of pressure, in such a manner that the circle which appeared last always surrounded the point of contact, and on a still further pressure extended its circumference while it contracted itself breadthwise, to form a kind of ring round a new circle that arose near its middle.

The pressure having been carried to a certain term, Newton stopped, and observed as follows: At the point of contact was a black spot that was encompassed by several series of colours. The order of the colours from the centre to the borders of the two glasses was this: In the first series, blue, white, yellow, and red; in the second, violet, blue, green, yellow, and red; in the third, purple, blue, green, yellow, and red; in the fourth, green and red; in the fifth, greenish blue and red; in the sixth, greenish

From these proportions, it was merely necessary to ascertain the absolute length of a single diameter, to know the lengths of all the others, as well as the different thickness of the plates of air at the points where the different colours were seen. Newton drew up a table of these degrees of thickness, by which it appears, that the most intense blue—for example, that of the first series—is expressed by a thickness of 0·000024 of an inch, supposing the visual ray to be nearly perpendicular to the two glasses.

716. Newton having measured also the diameters of the rings at the intermediate places where the colours were obscure, found that their squares were to one another as the even numbers 2, 4, 6, 8, 10, 12, &c.; and hence the intervals between the glasses, at the corresponding points, observed a similar progression.

717. The diameters of the rings increased or diminished, as the visual ray was more or less inclined to the surface of the two glasses, so that the greatest contraction took place when the eye was situated perpendicularly above the glasses. The diameters also retained the same proportions to one another.

718. Such were the phenomena which the glasses seen by reflection presented; but on looking through them to observe the effect of refracted light, other series of colours took place of the preceding ones. The central spot became white, and the order of co-

---

bi-convex glass that turns towards an belongs. Let also ab, ad, be the semi-diameters of two rings at the points where the colours are most vivid. Having drawn be, dg, parallel to the diameter af; and eh, gi, parallel to an; we shall have, by the property of the circle, $(eh)^2 : (gi)^2 :: ah \times hf : ai \times if :: ah \times af : ai \times af :: ah : ai :: be : dg$, the lines hf, il, being deemed equal to the diameter af, because ah, ai, which measure the intervals, be, dg, between the glasses, are supposed to be nearly infinitely small with respect to the diameter.

lours, relatively to the different series was this: in the first, yellowish red, black, violet, blue; in the second, white, yellow, red, violet, blue; in the third, green, yellow, red, blueish green; in the fourth, red, blueish green; in the fifth and sixth, the same two colours. By comparing these colours seen by refraction, with those which were the consequence of reflection, it is observable, that the white answers to black, the red to blue, the yellow to violet, the green to a mixture of red and violet: that is, the part that appeared black on simply looking at the glasses, became white when the observer looked through them, and so of the other colours. But the tints produced by refracted light were feeble and languishing, unless the visual ray was extremely oblique, in which case they were sufficiently vivid and brilliant.

719. Newton substituted water for air between the two glasses, and the colours instantly became fainter, and the rings contracted, that is, the ring of a particular colour had its circumference nearer the centre, than when that colour was reflected by the plate of air *. The diameters of the corresponding rings were to one another nearly as 7 is to 8, and consequently

colour is perceived, is to the interval which gives that colour, by means of air, as the sines which measure the refraction, at the passage from the same medium into the air. This rule may be equally applied to a thin plate detached from any kind of body, the thickness of which we would determine by the tone of its colour. We shall presently give an example of the method that should be pursued in determinations of this sort.

720. Newton varied the experiment in several ways. He fixed his attention on the colours of the bubbles that are produced in soapy water, dilated by the air that is introduced by blowing through a tube *. He observed the changes they underwent in proportion as the aqueous pellicle, of which each bubble was formed, became thinner, by the subsiding of the water from its upper part; he saw also the rings composed of these colours dilate, as they were more remote from the summit of the bubble, when he looked at them more obliquely; but this dilatation was much less, *cæteris paribus*, than when the colours were reflected by air. From this and a number of other observations, he inferred, that when the coloured substance had a density incomparably greater than that of the surrounding medium, the change of obliquity in the direction of the visual ray occasioned no change that was perceptible in the position of the colours, so that every part, seen in the same degree of inclination, constantly preserved its colour.

721. In all these experiments, the various series of colours, produced by reflection or by refraction, differed more or less from one another, either in number, or combination of tints. Newton, by means of a new experiment, succeeded in separating the effects

---

* Optice Lucis, book ii, part 1, observ. 17.

of the different homogeneal colours that contributed to the total effect, and in some sort accomplished the analysis of the phenomenon.

Having placed the two object-glasses in a dark room, where he introduced a ray of light, he so disposed a prism, that by turning it on its axis, it caused the different colours refracted by it to fall successively, sometimes upon a sheet of paper that reflected them towards the glasses, and sometimes directly upon the glasses themselves *. By this process each colour exhibited its effect separately from the rest: and during the motion of the prism, there appeared in turn several sets of concentric rings, which were all of the same colour for the same position of the prism. The red rings had their diameters perceptibly larger than the violet rings; and Newton says, that "it was very pleasant to see the rings gradually swell or contract accordingly as the colour of the light was changed." It resulted from this observation, that violet was the colour which gave in general the smallest rings, and that afterwards the diameters gradually crossed one another, in the order in which the other colours presented themselves, that is to say, numbers, 1, 3, 5, 7, 9, &c.; and the squares of the diameters of the rings, produced by the refracted colour, were as the even numbers, 2, 4, 6, 8, 10, &c.

722. Now, when the two object-glasses were exposed to the light of day, the different colours of which this light was composed, formed all at once their rings at the same distances as when they acted separately in the second experiment; and if these distances had been such, that the rings of different colours could not have infringed upon one another, each series would have presented as many distinct colours; but the rings having their breadths more or less sensible, and being pressed more or less together, in the space they occupied, were confounded, at least in part, at certain places, and especially in the first series, which included a small annular band of a vivid white, resulting from the mixture of all the colours. In each of the following series the colours were in general more distinct; but beyond a certain term some of the adjoining series encroached upon the others; and hence the colours, sometimes simple or nearly so, and sometimes more or less mixed and variously shaded, which the different series successively presented. The rays, which were refracted in the intervals of the rings formed by the reflection of the isolated colours, combined in a similar manner, so that a particular degree of tenuity in a given point of the plate of air, had a fitness at once both for the reflection of a particular colour simple or mixed, and for the transmission of some other colour.

All the colours decayed and vanished at a certain distance from the centre, because the different rays, by mixing nearly in equal proportions, produced only a whitish light.

723. It is not necessary that the plate which exhibits the coloured ring should be a fluid matter,

Portions of a solid body, reduced to a sufficient degree of tenuity, have the same property. It is possible, for example, to render a plate of mica so thin, that it shall be capable of reflecting one or more of the colours which the plate of air presents in the first experiment. And it is remarkable, that the colours in question do not in themselves depend upon the nature of the surrounding medium; for, wet the plate of mica, and those colours will merely become weaker than when the mica was encompassed with air; it is their intensity only that is changed.

This leads us to mention some experiments made by Mazeas, the results of which do not agree with the explanation Newton gives of the phenomenon of the coloured rings *. In these experiments the two glasses, placed one on the other, did not exhibit the same appearance when they were put under a receiver exhausted of air, or were exposed to a heat sufficiently strong to expel that fluid from the intermediate space. To this it might be answered, that, in the first case, a perfect vacuum cannot be obtained; and that, supposing it possible, the space between the glasses in the second case is occupied at least by caloric: in plate of air or any other substance, the *returns* or *fits of easy reflection*, and the disposition of the same ray to be transmitted in the same manner through the intervening spaces, *returns* or *fits of easy transmission.* Thus, a ray is in a fit of easy reflection when it falls on a plate of any kind of matter, whose thickness is one of the terms of the series, 1, 3, 5, 7, 9, &c. taking the smallest thickness capable of reflecting such ray for unit; and, in like manner, it is in one of its fits of easy transmission when the thickness is one of the terms of the series, 2, 4, 6, 8, 10, &c.*

725. Let us attend to the consequences which Newton derives from all these observations relative to the colouration of bodies. The particles even of those bodies which we call opake, are in reality transparent: this, persons who are in the habit of using the microscope must continually perceive. The thin edges of the darkest flint will appear, even to the unassisted sight, to have a certain degree of transparency if placed between the eye and the light; and as to white metallic substances, which at first would appear to be exceptions, Newton observes, that by the action of an acid they may be so attenuated as to render their particles permeable by light †.

In every body, the particles are separated from one another by interstices called *pores*, which are occupied by different subtile fluids. These particles having a determinate thickness repel the rays that, in penetrating them, are in a fit of easy reflection; and the body thus assumes the colour, simple or mixed, which answers to that of the reflected rays, and depends upon the degree of tenuity of the particles.

In reality we have seen (723) that the coloured rings took place equally in plates of solid bodies, as in those of liquid or fluid ones; and since every little space, included in one of these plates, reflects or refracts light, it follows, that if we divide this plate into a number of small fragments, each of these fragments would still produce the same effect as when it formed part of the plate. Now, as the particles of a body may be compared to the separated fragments of a plate, all that has been said of such plates applies exactly here.

---

* Optice Lucis, book ii, part 3, propos. 13, *definitio.*

† Ibid. book ii, propos. 2.

726. In speaking of the particles of bodies, we do not pretend to designate their smallest parts, or those which we call integrant moleculæ. To conceive what ought to be understood by the particles that reflect light, we may suppose, with Newton, that the integrant moleculæ, already separated from one another by pores, form, by a certain number uniting together, other moleculæ of a second order, separated by larger pores; that these in their turn form moleculæ of a third order, and so on*. Now the particles which reflect light, in the usual state of a body, have a certain thickness, whence arise separations between them of a certain extent: these particles are then deemed

alone. If you divide this plate into thinner ones, as far as a certain degree of tenuity, you isolate particles of another order, which will reflect other colours, as is confirmed by observation.

727. We have mentioned, in the article of divisibility (16), a plate detached from a piece of mica, whose tenuity was such, that its original colour, which was a yellowish white, changed to the most perfect blue. We are now capable of understanding how the properties of light may be employed to seize those small portions that escape our most accurate mechanical methods. According to Newton, the thickness of the plate of air, where the pure blue was reflected in the phenomenon of the coloured rings, was 2·4 millionths of an English inch. Now from the principle stated above (719), the thickness of the plate of mica of which we have spoken, must be to the thickness of the plate of air, as the sine of incidence is to the sine of refraction, when the light passes from the mica into the air; but as mica does not so readily yield to experiments that would immediately give its law of refraction, we supply the defect by means of that further observation of Newton, that the refractive powers of substances are nearly proportional to their densities (668), provided the substances are either both inflammable or both not inflammable.

This being laid down, let *c r* (fig. 109) be a ray of light meeting the surface of a piece of mica under an infinitely small angle, and let *r g* be the refracted ray, the direction of which might be determined, if the mica had at the same time sufficient thickness and transparency to render the determination possible. In the same hypothesis, let *r g′* be the refracted ray relatively to a second substance, whose refractive power we know, and which will serve as a term of comparison. We have chosen, for this effect, sulphate of lime, the refractive power of which, according to Newton, is such, that if we designate the constant quantity rn by unit, we shall have $(g'n)^2 = 1{\cdot}213$.

Now the density of mica, determined by its specific gravity, is to that of sulphate of lime as 2·792 : 2·252. Therefore we have $(g'n)^2$ or $1{\cdot}213 : (gn)^2 :: 2{\cdot}252 : 2{\cdot}792$. Working by logarithms, we shall find for that of gn, ·886039, whence we shall conclude that the angle of refraction, rgn, is 39° 11′; and because, in the present case, the angle of incidence is a right angle, the proportion between the sines, when the light passes from mica into the air will be that of the sine of 39° 11′ to the radius. Now this proportion being the same as that which exists between the thickness of the plate of air expressed by 2·4 millionths of an inch, and the thickness of the plate of mica which reflects a fine blue, we shall obtain for this last 1·511 millionth of an inch English, or about 1·6 millionth of an inch French, that is to say, nearly 43 millionths of a millimetre[*].

728. The disposition of a ray to be reflected or refracted by any particle of a body, depends at once on the two surfaces of that particle, since there is only one distance, greater or less, between these surfaces, such that the ray may not be reflected instead of being refracted, and *vice versa*. Hence it is, that if we wet either face of a very thin plate of any substance, such as mica, the colours instantly become feeble; from which we must infer, that the reflection or refraction takes place near the second surface; for if it took place next to the first, or before the ray had

---

[*] According to the Encyclopédie Méthodique, Mathematiques, vol. II, second part, p. 580, the difference between English and French measure is such, that the English foot is equal only to 11 inches 4 lines $\frac{1}{2}$, or $\frac{273}{2}$ lines of the French foot.

penetrated the particle, the second surface would have no influence either on the reflection or refraction of this ray. Besides, the disposition of which we are speaking is propagated and perseveres in the ray, from the first surface to the second; or else, when the ray arrived at the second surface, the first would have no concern in the action that determines it to be reflected or refracted *.

729. The colour of a body is the more vivid and pure, other circumstances being equal, as to the surrounding mediums, in proportion as the moleculæ of that body are thin; in the same manner as in Newton's experiment, the thinnest parts, or parts nearest the centre, were those where the colours appeared with the most strength and splendour. Among the moleculæ that reflect colours of a single order, those which furnish red are the thickest, and those which give violet, the thinnest.

730. Nature exhibits in several stones a phenomenon similar to that of the coloured rings. Of this number is the opaline agate or opal, which, in the reflections of light which it darts from its interior, seems to unite the tints of the ruby, topaz, emerald, and sapphire, and to sparkle with peculiar brilliancy. This stone owes its beauty simply to its imperfections, and to the multitude of cracks and flaws which intercept the continuity of its proper matter, and form vacuities occupied by a subtile fluid that is probably air. The small plates of this fluid are in the same case precisely as the plate of air between the glasses in Newton's experiment: the colours also of the opal disappear the instant it is broken (*x*).

---

* Optice Lucis, lib. ii, pars. 3, propos. 12.

(*x*) The first distinct account of the colours exhibited by thin plates of various substances, is met with among the observations of Mr. Boyle. To shew the chemists that colours may be made to appear or vanish, where

Carbonate of transparent lime, sulphate of lime, rock crystal, &c. also frequently exhibit in their interior reflections of divers colours, which must in like manner be attributed to the slight cavities natural to the stone, or produced in it by percussion.

731. The density of the moleculæ of bodies in general greatly exceeds that of the mediums which occupy the interstices between their component laminæ, and that of the air which surrounds these bodies. Hence it is that the colours of the same bodies viewed in different degrees of obliquity undergo no perceptible change; but if we suppose the plates to have scarcely more density than the surrounding mediums,

---

there is no accession or change either of the sulphureous, the saline, or the mercurial principle of bodies, he observes, that all chemical essential oils, as also good spirit of wine, being shaken till they rise in bubbles, appear of various colours; which immediately vanish when the bubbles burst, so that a colourless liquor may be immediately made to exhibit a variety of colours, and lose them in a moment, without any change in its essential principles. He then mentions the colours that appear in bubbles of soap and water, and also in turpentine. He sometimes got glass blown so thin as to exhibit similar colours; and observes, that a feather, of a proper shape and size, and also a black ribbon, held at a proper distance, between his eye and the then a change in their position, however slight, will cause their colours to vary [*].

To find the reason of this difference, let us suppose *a b l k* (fig. 110) to represent the section of a plate of any substance, the density of which is incomparably greater than that of the medium which surrounds the plate. In this case, a ray of light, *r c*, which shall meet the surface of the plate under any obliquity, will be refracted in its interior, according to a direction, *c i*, which will deviate very little from the perpendicular, *u n*, at the point of immersion, on account of the extreme difference between the sine of incidence and the sine of refraction. Let another incident ray, *r′ c*, meet the same surface in an obliquity perceptibly different; the refracted ray, *c o*, will deviate but little more from the perpendicular *u n*, and of consequence

---

colour, and that these plates will be found upon examination to be of the same thickness throughout.

As a fact similar to this, but observed previously to it, we may here mention that Lord Brereton, at a meeting of the Royal Society in 1666, produced some pieces of glass taken out of a window of a church, both on the north and on the south side; observing, that they were all eaten in by the air, but that the piece taken from the south side had some colours like those of the rainbow upon it, which the others on the north side had not. This phenomenon has been frequently observed since, and in other circumstances. It is not to be doubted, but that in all these cases the glass is divided into thin plates, which exhibit colours, upon the same principle with those which are above described by M. Haüy.

A paper of Dr. Herschel's has, during the present year (1807) been read before the Royal Society, on the coloured concentric rings seen through thin plates or lenses: we understand that the doctor's experiments were made in great variety, with lenses of from 120 feet focus down to those of the most usual size and shape: but his results and deductions we are not able to communicate.

Dr. T. Young has contrived an apparatus for exhibiting and measuring the colours of thin plates by means of the solar microscope; a description of which is given in the *Journals of the Royal Institution*, I. 241, and in *Nicholson's Journal*, 8vo. vol. III. pa. 283.—Tr.

[*] Optice Lucis, lib. ii, pars. 3, propos. 6.

the spaces between *a b* and *k l*, measured by the two refracted rays will only differ in a small degree; from which it follows, that the colours which depend on these spaces will experience but a slight change. Let us suppose, on the contrary, that the density of the plate *a b l k* nearly approaches to an equality with that of the surrounding medium: in this case, the incident rays *d g*, *s g*, will undergo but a slight inflection in crossing the plate; so that the refracted rays *g p*, *g m*, being nearly in the direction of the incident rays, there will result a very considerable difference between the spaces measured by these rays, and also between the colours relating to those spaces.

732. This may enable us to understand the changes which the colours of certain bodies undergo, when placed in different positions with regard to the eye; such as those which embellish the plumage of many birds, and particularly that of the peacock. These colours, already so splendid and various when seen in one aspect, are still more diversified by becoming moveable with the bird himself, every change of position producing a play of the most brilliant reflections of light, that disappear in another position to be supplied by new reflections, while the first are reproduced in a different part of the plumage. These beautiful appearances are all the result of this circumstance, that the beards of the feathers, which are inserted laterally on the branches, have a tenuity that enlivens the colours, and a density at the same time, which, not greatly exceeding that of the surrounding medium, occasions the position of these colours to vary, as the obliquity of the visual ray itself varies *.

The effect we have just stated takes place also in the experiment of the coloured rings (717), though there the plate of air comprised between the glasses is incomparably less dense than the substance of the glasses; but the reason is, that the light, in this case, by deviating considerably from the perpendicular, in passing from the glass to the plate of air, assumes positions whose obliquity changes very sensibly, as the position of the visual ray inclines more or less, which occasions the densities measured by the refracted rays to vary proportionally. This effect is the reverse of that represented by figure 110, where *r c*, *r′ c*, are considered as incident rays, and *c o*, *c i*, as refracted rays. For it is evident, that if, on the contrary, these last lines were supposed to be the incident rays, a variation, however trifling, in their directions, would occasion a very considerable one in that of the refracted rays *c r*, *c r′*.

---

* Optice Lucis, lib. ii, pars. 3, propos. 5.

733. From the principles we have stated, it is easy to account for the colours produced in certain liquors that have themselves no perceptible colour, by mixing one of these liquors with another, or for the changes of colour that a liquor naturally coloured experiences in the same case. Thus nitrous acid poured into alcohol, into which a few rose leaves have been infused, but not in sufficient number to give it their tinge, developes all at once a colour similar to that which the rose leaves had previously to their infusion. The same acid mixed with tincture of turnsole changes blue into a lively red. By the addition of an alkali, syrup of violet becomes green. In all these changes the union of the moleculæ of the two liquids, forms mixed moleculæ, the thickness of which is different from that of the component moleculæ, and determines the reflection of the colour answering to that thickness.

734. Let us now consider the fits of easy reflection and easy transmission in transparent bodies, and let

us begin with those which are limpid and colourless. The particles of these bodies exceed in tenuity the smallest thickness capable of reflecting light, and of consequence the rays which penetrate the moleculæ at the surface are transmitted; for these moleculæ are precisely in the case of the small plate of air situated near the contact of the two objects, in the experiment of the coloured rings, which transmitted all the colours without reflecting any. The rays which have penetrated a limpid medium continue their course through its whole thickness, without a single one being reflected on contact of the moleculæ with the subtile media included in the pores, as if these moleculæ formed with one another a perfect continuity. During their whole course, the rays notwithstanding preserve their disposition to be reflected or refracted, by virtue of the fits of easy reflection or easy transmission, in such manner that if we express by *t* a certain thickness which would have occasioned the reflection of a particular species of ray, where the medium would only be of that thickness, that ray will preserve a tendency to be reflected at every point

Neither tendency produces its effect except when the light has reached the second surface of the body. There, all that part of the light, which, on account of the distance between the two surfaces, or of the number of intervals, is in a fit of easy reflection, becomes reflected near the contact of the second surface with the adjoining medium; and the part which is in a fit of easy transmission becomes refracted on passing into the adjacent medium: so that if the medium were of a different thickness, which might give for each fit a unit more or less, the rays would change their office, those which would have been in fits of easy reflection, would be in fits of easy transmission, and *vice versa.*

We hence see why a part of the light is always reflected at the contact of two mediums of different density, by escaping the refraction which the other part experiences (647).

735. In what we have thus far said of the subject of fits, we have considered only what takes place in the path of the rays from the first surface to the second; but reflection brings back a portion of the rays from the second surface to the first, and it is proper to enquire what their disposition will be during their return, and what the nature of their fit when arrived at the first surface.

To investigate this point of theory, let us take up things at their origin, and suppose *a b, c d,* (fig. 111), to be exactly parallel faces of any medium denser than air, and surrounded by that fluid. Let *g n* be a beam of light which falls on the surface *a b*. Among the rays composing this beam, some will be in a fit of easy reflection, and of consequence will be reflected according to *n x*, inclined in the same degree as *g n*, but in the contrary way; while others, being in a fit of easy transmission, will be refracted according to *n o*.

The species of fit will be determined by the kind of intervals through which each ray will have passed in the air; so that if the radiant point be in the middle of this fluid, all the rays respecting which the course, from that point to the point *n*, shall be comprised in the series 1, 3, 5, 7, &c. will be reflected, unity representing here the smallest thickness of air capable of reflecting each ray; and all those rays whose course shall be comprised in the series 2, 4, 6, 8, &c. will be transmitted according to *n o*.

These last rays being then in a different medium, where the intervals are no longer the same, some, on arriving at the point *o*, will be again in a fit of easy reflection, and will be repelled in the direction *o r*, the angle *r o c* being equal to the angle *n o d;* while others will be in a fit of easy transmission, and will repass into the air in the direction *o z* parallel to *g n*.

But, as we suppose the lines *a c*, *b d*, to be perfectly parallel, it results, that the rays reflected according to *o r* traverse a space equal to what they had traversed in the direction *n o*. Now the intervals of easy reflection measured by the ray proceeding in the direction *n o*, or, which amounts to the same thing, the di-

distances, from the point *o* only, they will form the progression 2, 4, 6, 8, &c.; but this progression is that which belongs to fits of easy transmission; therefore the ray, during its whole course according to *o r*, is in the precise case where one of the rays, after traversing the line *n o* equal to *o r*, becomes refracted, on repassing into the air according to the direction *o z*. Hence the ray *o r* will itself be refracted at the point *r*, in a direction, *r s*, which will make with *a b* an angle equal to that which *n g* forms in a contrary sense with the same line.

We hence conclude that the rays which are reflected at the second surface of a medium, undergo in their return towards the first the inverse effects of those which took place in the course from the first to the second; so that after reflection, fits of easy transmission succeed to those of easy reflection *.

This will be the case, whenever the series of intervals that answer to *o n* shall be terminated by an even number; but if the two faces between which the light moves were not exactly parallel, or had sensible inequalities, then among the rays reflected according to *o r*, those which would have to traverse an interval greater or less by unit, to return to the surface *a b*, would be reflected anew towards *c d*, while the rest would be transmitted by the surface *a b*.

736. What has just been said enabled father Boscovich to obviate an objection raised by himself against the explanation that was given of the exterior rainbow †. It is this: Let *n g* (fig. 112) be one of the drops of rain which produce that bow, and *s h g f n a* the course of a beam of rays, of any colour,

---

* Optice Lucis, lib. ii, pars. 3, propos. 19.

† Mém. des Savans étrangers, vol. III.

taken among the effectual rays: this stream having passed from *h* to *g*, has a part of its rays transmitted into the surrounding air, and the rest are reflected according to *gf*. But the rays which entered at the point *h* were in a fit of easy transmission, and those which were reflected at *g*, in a fit of easy reflection. Now the chord *gf* being equal to the chord *hg*, measures the same series of intervals; and since the rays which proceed from reflection at *g* to reach *f*, experienced effects the reverse of those which had taken place in proceeding from reflection at *h*, it follows, that they must be in a fit of easy transmission at *f*, and consequently there ought to be none of those rays at *n* which should otherwise be reflected from *f*; but they would all issue at that point, which would render the formation of the exterior bow impossible.

To this father Boscovich replied by observing, that the difficulty arose simply from supposing the drops of rain to be spherical, which there is no ground for presuming, for this reason alone, that every drop must be compressed a little in its lower part, by the reaction of the air against which it strikes in falling. Now the slightest difference between the chords *hg*, *gf*, is sufficient to occasion a unit more or less on one side than on the other in the intervals measured by these chords, and to cause the ray arrived at *f* to experience a new fit of easy reflection; in which case it will take the direction *fn*, and will be at *n* in a fit of easy transmission, which will occasion it to repass into the air in the direction *na*.

737. Light which traverses a transparent medium does not arrive entire at the second surface of that medium; which arises solely from this circumstance, that there are always rays intercepted by the medium, where they are extinguished by striking against the

real molecula of that medium; and the number of these intercepted rays increase continually during the whole course of the light.

It follows from this, that the intensity of light on a given space, in proportion as it removes from the radiant point, is not exactly in the inverse ratio of the square of the distance, but follows a law that in a certain degree differs from it.

Bouguer has endeavoured to ascertain this law, by supposing, first, the medium to have a uniform density, and the rays to be parallel. In this case he proves the intensity of light to follow a geometrical progression. He afterwards extends his theory to média of a variable density, and to the hypothesis of a divergence between the rays, and makes many interesting applications of the theory to various phenomena *.

738. The opacity of bodies which have that quality arises not only from the moleculæ of those bodies extinguishing and absorbing light, but also from the moleculæ being separated by a number of interstices filled with some fluid that has a much less density than theirs; whence it results, that there are a number of rays which are repelled near the contact of the surfaces of the moleculæ and the adjoining medium; and as the reflections rapidly increase, in proportion as the rays penetrate the body, it happens that they soon escape from the refraction which should propagate them from one surface to the other, that the body might be transparent †.

739. This leads us to explain how the stone called the *hydrophanous agate* acquires a perceptible transparency when it has been plunged into water, and is

---

* Bouguer, Traité d'Optique; Paris, 1760, p. 231, et seq.

† Optice Lucis, lib. ii, pars. 3, propos. 3.

then placed between the light and the eye. We have seen (9) that this stone is pierced with a multitude of vacuities, which, in the natural state of the stone, are filled with air. The little density of this fluid, compared with the proper matter of the stone, occasions the reflection of a great part of the rays which penetrate it, and leaves but a slight degree of transparency, the result of the small number of rays which pursue their course to the surface that is turned towards the eye. But if, instead of air, water be introduced into the hydrophanous agate, this liquid being of a density which approaches much nearer to that of the stone, there will be a great number of rays, which, instead of being reflected at the contact of the media that succeed each other in the interval between the two surfaces, will be refracted, and will continue their course as far as the surface situated towards the eye, which will cause the transparency to increase in a very considerable proportion. Paper wetted with water, or that has imbibed oil, also acquires transparency, for a similar reason.

740. With respect to bodies that are both transparent and coloured, they appear to furnish a sort of middle term between limpid bodies and opaque bodies. Their moleculæ reflect rays of the colour under which they present themselves to the eye, and these bodies at the same time transmit, through their whole extent, other rays, which commonly have the same colour as the reflected rays. Thus the moleculæ situated at the surface reflect a portion of the rays which reach this surface and transmit the rest; other moleculæ situated a little lower, reflect a portion of the rays which escaped the first reflection, and transmit the remainder, and so regularly on to the last surface, where there still arrives a sufficient number of rays that repass into the air for the body placed be-

tween the eye and the light to have a very sensible degree of transparency. Hence it follows, that the thicker the medium, the deeper the colours; which agrees with observation.

741. There are media that present a different colour accordingly as they are seen by reflection or refraction, as in the case of each of the small spaces in the plate of air, in the experiment of the coloured rings. It is thus with infusion of lignum nephriticum (y), which appears blue in the ordinary aspect, and becomes yellow when the vessel containing it is placed between the eye and the light. A plate of gold extremely thin continues to reflect yellow, yet appears of a greenish hue when seen by refraction.

(y) Mr. Boyle describes this lignum nephriticum to be a whitish kind of wood, that was brought from Mexico, which the natives call *coatl* or *tlapazatli*, and which had been thought to tinge water of a green colour only; but he says, that he found it to communicate all kinds of colours. If, says he, an infusion of this wood be put into a glass globe, and exposed to a strong light, it will be as colourless as pure water; but if it be carried into a place a little shaded, it will be a most beautiful green; in a place still more shaded, it will incline to red; and in a very shady place, or in an opaque vessel, it will be green again.

A cup of this remarkable wood was sent to Kircher by the procurator of his society at Mexico, and was presented by him to the emperor as a great curiosity. It is called *lignum nephriticum*, because the infusion of it was imagined to be of service in diseases of the kidneys and bladder, and the natives of the country where it grows use it for that purpose.

Boyle corrected several of the hasty observations of Kircher concerning the colours that appear in the infusion of lignum nephriticum, and he diversified the experiments with it in a very pleasing manner. He first distinctly noted the two very different colours which this remarkable tincture exhibits by transmitted and reflected light. If, says he, it be held directly between the light and the eye, it will appear tinged (excepting the very top of it, where a sky-coloured circle sometimes appears) almost of a golden colour, unless the infusion be too strong; in which case it will be dark or reddish, and requires to be diluted with water. But if it be held from the light, so that the eye be between the light and the phial, it will appear of a deep lovely blue colour; as will also the drops, if any lie on the outside of the glass.—Tr.

But these phenomena, and others resembling them, to use Newton's expression, ***have no longer need of an Œdipus*** *.

742. We see how much the observation of the coloured rings serves to link together different facts in the same theory; but it were greatly to be wished that this theory extended farther, and explained, on some hypothesis or other, why some rays are transmitted and others reflected by the same thickness of a given plate. We will suppose, if you please, with Newton †, that it is with rays of light relatively to certain natural bodies, as it is with sonorous bodies in regard to air, that is, that the rays excite in the moleculæ of bodies which refract or reflect them, certain vibrations that are propagated from one surface to the other, but in such manner that their velocity is greater than that of the rays themselves, so that, if we may so express ourselves, they get the start in the race. Now as these vibrations consist of slight motions that take place alternately in a contrary sense, if, at the instant the ray arrives near to contact with the reflecting or refringent surface, its vibratory motion conspires with that of the body, the ray will be transmitted; but if

rise to refraction. Newton however suggests this idea merely for the satisfaction of those who are solicitous to find a physical cause for the facts on which the theory rests. For himself, he is contented with having established their existence and filiation. Philosophers, who wisely stop at the limit traced by observation, will derive sufficient satisfaction from a theory that refers the infinitely-varied phenomena of the coloration of bodies to the simple distances between the facets of the moleculæ, and which exhibits that admirable diversity of tints and shades with which the productions both of nature and art are embellished, in the manner of a picture, where we have only to give a new degree of tenuity to the canvas, to create instantly a new colouring (z).

(z) After all, we must be free to confess, although we should with extreme reluctance call in question any doctrine of Newton, that his theory of reflection is highly objectionable: in fact, it explains nothing, unless the *cause* of the fits of more easy reflection and transmission be admitted as legitimate, namely, that they are produced by the undulations of *another elastic fluid incomparably more subtile than light*, acting upon it in the way of impulse: but, to admit any thing of this kind, would, we conceive, be to transgress the rules of philosophising prescribed by Newton himself, and to return back many steps towards the exploded absurdities of Descartes and Leibnitz.

Before we entirely quit the subject of colours, it may be proper to mention that several philosophers have recently contemplated the doctrine of colours in connection with chemistry, and the art of dyeing. Among others Bertholet, in his *Elemens de Teinture*, adduces many arguments from which he infers, that we must not confound the fugitive colours that are produced by the reflection of laminæ, and conform to the laws determined by Newton, with the colours which are still preserved notwithstanding the changes of density and thickness. This celebrated chemist likewise remarks, that the three primitive colours in the arts develope themselves in the bodies of the three kingdoms by a less or greater absorption of oxygen which combines with the different principles of those bodies.

In its natural state, iron is without colour. The first impression of fire, or the first degree of oxydation, developes a blue colour; a second degree of oxydation produces yellow: if the oxydation augments, the iron becomes red. The major part of *metals* present similar phenomena.

Relations between Light and Heat.

In the account we shall give of the relations that in many respects exist between light and caloric, we shall confine our attention to facts, without pretending to draw any inference from them as to the identity of causes. We have deemed this the properest place to introduce the subject, because in the experiments we have been detailing, by employing coloured light as a term of comparison, some addition has been made to the knowledge we possessed of the relations in question.

743. We know that the solar rays give heat, in

In *vegetables*, the blue is formed by fermentation, that is to say, by a fixation of oxygen; and most of these colours are susceptible of passing to red by a greater quantity of oxygen. It is thus that turnsole is reddened by air and by the action of acids.

The same colours are seen to develope themselves in *animals*, by the combination of oxygen. When meat putrefies, the first degree of oxydation decides the blue colour; the red colour soon succeeds it as the oxygenation augments. This phenomenon is very perceptibly manifest in the preparation of cheeses, which are covered first with a blue mould, that afterwards becomes red.

general, to bodies exposed to their action; but they do not communicate it in the same degree to all bodies; and Scheele, with his usual sagacity, has discovered the circumstance which occasions the intensity of their action to vary, and the principle that enables us to explain the variation. This celebrated chemist having exposed to the action of the solar rays two thermometers, one filled with alcohol coloured of a deep red, and the other with uncoloured alcohol, observed that the red liquor rose more rapidly than the other; but if the two thermometers were plunged into hot water the motion of the liquor was the same in each. Scheele remarked also, that the nearer the colour of a body approached to black, the more readily was that body heated by the sun's rays; and, on the contrary, that the whitest bodies were those which were heated most slowly. He adds, that "the cause of these phenomena is the greater or less affinity which bodies have to light [*]."

744. We observe here a striking analogy between light and radiant caloric, which is only capable of giving heat to a body by losing its radiant property, and assuming, by its union with that body, the character of combined caloric (118, et seq.) In the same manner, as long as the motion of light is uninterrupted, no heat, properly speaking, is derived from it [†]; and if this motion merely changes its direction from the effect of reflection, the rays so altered in their motion do not contribute to the production of heat, which depends wholly on absorbed rays. Hence it is, that bodies which absorb the most light, as black ones, for instance, are those which are most heated,

---

[*] Traité Chimique de l'Air & de Feu, translated by Baron de Dietrich, Paris, 1781, p. 146.

[†] Scheele, ibid.

while light operates much more feebly on white bodies, because they reflect it (*a*).

745. There is however between light and caloric, this difference, that the rays of the first traverse glass and limpid liquors freely, while the rays of caloric remain engaged in the bodies to which they communicate heat[*].

746. The learned Rochon attempted, in the year 1775, to ascertain, by experiment, if the rays which differ in refrangibility produced on the thermometer degrees of heat that were sensibly different[†]. He made use of a prism of flint glass, to separate the differently coloured rays, which he afterwards caused to pass in turn through a lens. He observed, that an air-thermometer, exposed to the action of these rays, rose in proportion as the rays followed one another, from violet to red; and the proportion of heat between clear red and the most intense violet appeared to him to be nearly that of 8 to 1. But he modestly owns, that, notwithstanding the precautions he took to obtain accurate results, he was not satisfied with his labour[‡].

747. The celebrated Herschel, whose name reminds us of so many important discoveries, has since undertaken an admirable set of experiments with the same

---

(*a*) Dr. Franklin made several experiments on the different degrees of heat imbibed from the sun's rays by cloths, &c. of different colours, shewing the gradations from black, blue, green, purple, red, yellow, to white; and, according to the happy method for which he was so deservedly celebrated, applied the results of his researches to useful purposes in common life. An account of these may be seen in his *Experiments and Observations*, and of some of the most interesting in a note in *Gregory's Lessons*, pa. 156, ed. iii.—Tr.

[*] Bertholet, Statique Chimique, vol. I, p. 192.

[†] Essai sur les degrès de chaleur des rayons colorés, Reçueil de Mém. sur la Mécanique & la Phys. p. 348, et seq.

[‡] Ibid. 355.

view, and has extended his enquiries to every object capable of furnishing a comparison between the physical properties of light and those of caloric. In the experiments relating to heat produced by the differently coloured rays of the solar spectrum, he made these rays pass in succession through a hole in a screen, and received them on the ball of a thermometer placed behind it. From what he observed, he concluded that the calorific power of the red rays was to that of the violet rays nearly as 7 to 2; a ratio much smaller than what was obtained by the French philosopher [*].

748. Herschel conceived the idea afterwards of comparing the rays of the spectrum with regard to their luminous force; and he judged that the red, which terminated the prism on one side, was surpassed by the yellow, which contained the *maximum* of brightness; that the green gave light nearly in the same degree, but that a diminution took place from that colour to the violet, which possessed the least luminousness [†]. These results differ but little from those which Newton had announced long before [‡].

The same astronomer endeavoured to ascertain the truth of a conjecture that had occurred to him in the course of his enquiries, which was, that there really existed, out of the limits of the solar spectrum, rays subject like the others to the law of refrangibility, but not luminous, and simply calorific. The conclusion he drew from his experiments was, that the faculty of giving heat had the same limits as the spectrum on the side of the violet; that it increased progressively from the violet to the red, and so beyond the red, where it resided in rays imperceptible to the eye and less refrangible than any of those that were luminous, in such manner that its maximum answered to the limit of about half an inch beyond the red *. From the hypothesis to which these experiments would lead, the emanations of the sun should consist of rays of two different kinds; some would be simply luminous, and others simply calorific: whence there would result two spectrums, that would in a great measure be confounded, so that the one produced by the luminous rays would get beyond the other on the side of the red; and the heat which accompanies light would depend on a mixture of the calorific rays. The author has also made a number of enquiries on the subject of heat produced by different luminous bodies, and by others that simply contained heat without luminousness; and it appeared to him, that the calorific rays were subjected to the same laws of reflection and refraction as those of light †. These different experiments are sufficiently interesting to merit a careful repetition, and sufficiently delicate to stand in need of it.

---

[*] Biblioth. Britan. vol. XV, p. 196, et seq.

[†] Ibid. p. 200, et seq. Phil. Trans. for 1800.

[‡] Optice Lucis, lib. i, pars. 1, propos. 7, exper. 16.

749. We know that light contributes greatly to chemical phenomena; and since, of its differently coloured rays some produce more heat than others, may they not also have a different influence in some of these phenomena, and particularly in those which depend on oxygen, whose functions so often correspond with those of caloric? Scheele, whose lot it would seem to take the lead in investigation, had observed, that muriate of silver exposed to the violet

---

* Biblioth. Britan. vol. XV, p. 217, et seq.

† Ibid. p. 293, et seq. See also vol. XIX, p. 19, et seq.

rays of the solar spectrum became black much more quickly than in the other rays *. Ritter, an able philosopher of Jena, has seen this substance become black in a short time even when out of the violet, then become less black in the violet, and lose its dark tint more as it approached to the red, where it no longer experienced any change (*b*). The same substance a little black, and exposed to the red light, recovered in part the white colour, and a still greater portion when presented to the invisible rays out of the limit of the spectrum on the red side. Phosphorus placed near the red instantly exhibited white vapours; placed afterwards near the violet, it no longer exhibited vapours, and was extinguished. These observations led the author to suppose, that the solar spectrum was comprised between two invisible rays, of which one, contiguous to the red, favoured oxygenation, and the other, contiguous to the violet, had the faculty of disoxygenating; and the intermediate coloured rays partook more or less of the action exerted by the invisible rays on each side.

750. Further experiments led the same philosopher to observe a remarkable resemblance between the effects of the differently coloured rays, with respect to oxydation, and those of the vitreous and resinous

---

* Traité Chimique de l'Air et du Feu, translated by Dietrich, p. 145.

(*b*) Dr. Wollaston also, in his paper on Refractive and Dispersive Powers (*Phil. Trans.* 1802), has proved the existence of invisible rays beyond the violet in the upper part of the prismatic spectrum, by the blackening of muriate of silver at that part. He likewise proves that the invisible rays have peculiar properties: for by narrowing the pencil of light received on his prism he made the discolouring rays fall almost entirely beyond the spectrum; and he hence infers, that the visible light has not this power, but owes its discolouring influence to the admixture of invisible light. It is but just to remark, that Dr. Wollaston's discovery appears to have been made without any previous knowledge of the experiments of Ritter.—Tr.

electricity produced by Volta's pile. We have seen that the first kind of electricity determined a metal to oxydate, while the other had no effect on oxydation (522). Ritter placed his eye in contact with the extremity of the pile that was in a resinous state, in which case the retina, according to him, acquired the opposite electricity, and the objects all appeared of a red tint; afterwards, applying his eye to the vitreous extremity of the pile, which made the retina pass to the resinous state, they all appeared purple to him (529, note *f*). This must be considered as a very interesting result, in which the organ of sight, subjected to the combined action of light and electricity, becomes as it were a common link joining together phenomena observed till then in isolated experiments, and with instruments that appeared to have no affinity with each other. A young Danish chemist of talents, Mr. Orsted, who was pleased to furnish us with these particulars, has added a very happy remark, that when the two opposite electricities produce, by uniting, white light, we have the proof as it were by synthesis, of what the preceding experiments have shewn by analysis.

4. *Natural Vision.*

751. We have considered light in three distinct points of view: first, as thrown out by the bodies of which it is an emanation; then as traversing space with a rapidity inconceivable, yet capable at the same time of being measured; and lastly, as received on the surfaces of bodies, of which some reflect and others transmit: and the study of the different modifications it undergoes, according to the different modes in which those bodies act upon it, has re-

vealed to us the causes of transparency, opacity, and colours.

The impressions which objects in their turn produce on the organ of sight, and which enable us to distinguish their different states, depend upon the immediate action exerted on that organ by the light which they transmit to it, whether it proceed directly from a luminous body, or have been reflected by the surface of a mirror or of an opaque body, or have passed through a transparent body.

Our object now will be to investigate the nature of that action, to trace the course which the rays transmitted by objects follow in the organ, and relate the results of the enquiries of different philosophers respecting the manner in which vision is effected. We shall begin with what is most simple, and suppose that between the eye and the objects there is no intermedium to modify the action of light.

Structure of the Eye.

752. The ancient philosophers had very imperfect notions of the manner in which vision is effected. They simply knew, in general, that the eyes were the instruments of it. Yet imperfect as were their ideas, the traits of wisdom and foresight did not escape their observation *. They admired the position of the eye in the most elevated part of the head, whence, like a sentinel, it could overlook a multitude of objects with a single glance. They admired its extreme mobility, and the ease with which it could turn in every direction, and thus multiply itself, in a manner, by the

---

* Cicero de Nat. Deor.

variety of its situations. They admired the suppleness of the lids, ready at all times to cover the eyes, as with a veil, to protect them from the impression of too vivid a light, or the attack of exterior objects, or to aid the power of sleep over all the human organs. But these and other observations of the same kind relate as it were only to neighbouring circumstances: the intimate mechanism of vision they had not thought of penetrating. It has since been discovered that every eye is a true optical instrument, on the ground of which light delineates, or rather paints, in miniature, the portrait of every object situated in the presence of the spectator: and of all the subjects of observation which Nature every-where presents to the eye, it may justly be said of this organ, that there is none which more forcibly exhibits in its structure the marks of Infinite Intelligence.

753. We shall begin the subject with a description of the eye, which, though not minute enough for the anatomist, will be sufficient for the philosopher to form an idea of the effects of vision.

The cavity in which the eye is lodged is called the *orbit of the eye*. The optic nerves which, separated as they proceed from the brain, are afterwards united in a common point, separate again, and each of them enters into the orbit on the side that corresponds with it, where it dilates to form the globe of the eye, so that the coverings of this globe are nothing else than expansions of the optic nerve.

In this nerve there are two principal tunics or coats observable one above the other round the medullary part. The exterior tunic, which is called the *dura mater*, assumes, in dilating, a round form, of which, the anterior part, which is without covering, represents nearly a spherical segment, of a smaller diameter than that of the part sunk in the cavity of the eye, which renders it prominent and better adapted to receive the rays that present themselves sideways.

Of these two spherical portions, that which occupies the bottom of the cavity is an opaque membrane of a considerable consistence; it is called the *sclerotica* or *opaque cornea:* the other portion, or the fore part, is thinner, more flexible, and diaphanous, and has therefore the name of the *transparent cornea.*

The second coat of the optic nerve is called the *pia mater,* and is extended underneath the *dura mater.* It is composed of two laminæ. Of these one, which is a real membrane, applies itself exactly on the opaque cornea, and becomes confounded with it near the transparent cornea: the other, which is called *choroides,* is an assemblage of nerves and vessels that issue from the internal surface of the first, and are pervaded with a sort of blackish liquor. These nerves and vessels open in part and form that velvet tissue of which Ruysch has made a distinct tunic, that goes by his name.

Towards the part where the transparent cornea joins the sclerotica, the choroides becomes detached, and is likewise divided into two laminæ, of which the anterior one produces that sort of coloured crown which is called the *iris,* having near the middle a perforation known by the name of the *pupil.* The posterior lamina, which is called the *ciliary corona,* is in folds, and composed as it were of oblong leaves, of which we shall presently see the use.

The iris is an assemblage of muscular fibres, some orbicular and ranged round the circumference of the pupil, others directed like so many radial lines. The use of the first is to contract the pupil, in order to moderate the impression of too strong a light, and of the others to dilate it, that a greater number of rays of a faint light may be admitted.

The most usual colours of the iris are orange and blue, and these colours are often mixed in the same eye. What are called *black* eyes are of a yellow brown, or a very deep orange.

The ciliary corona holds inclosed, as it were, opposite the aperture of the pupil, a transparent body, tolerably solid, of a lenticular form, and more convex towards the bottom of the eye than in front. This body is called the *crystalline humour*.

The medullary portion of the optic nerve forms, in dilating, a white and very thin membrane, applied upon the choroides, and called the *retina*.

The space between the transparent cornea and the crystaline humour is divided by the iris into two chambers, that have a communication by means of the pupil, and are filled with a limpid water, called the *aqueous humour*. Between the crystalline humour and the back part of the eye is another much larger space, filled with a sort of transparent jelly, which is the *vitreous humour*. The crystaline humour is set as it were in the foremost part of this gelatinous substance, the refractive power of which is less than that of the crystaline.

What is called the *white of the eye* is produced by a particular tunic, denominated *albugineous*, which strongly adheres to the cornea: it is covered by another thin, loose, and flexible membrane, called the *conjunctive tunic*, which turns back at the border of the orbit and forms the internal surface of the eyelids. It has a multitude of little perforations through which the fluid passes that comes from the lachrymal gland.

The eye is provided with different muscles destined to help it forward or draw it back, to enlarge or contract its opening, and to give it a variety of positions, that it may be able to perceive distinctly objects situated at different distances.

Manner in which Vision is effected.

754. From all the points of any object that presents itself to the eye, there proceed rays that diverge in every way; but of these rays, such as are directed so as to be able to enter the small aperture of the pupil form kinds of thin pencils, in such a manner that the rays of any single pencil are nearly parallel. Let us suppose the object, being of an elongated form, to be situated horizontally; and, for greater simplicity, let us consider only the pencil that comes from the middle, and the two that come from the extremities. The axis of the first pencil passing through the centre of the cornea, and falling at right angles on the surface of the crystaline humour, penetrates the different humours of the eye without undergoing refraction in them. This axis bears the name of the *optic axis*, and is of great use in explaining the phenomena of vision. The other rays which fall obliquely on the cornea are refracted in the aqueous humour, by converging towards the axis. Their passage through the crystaline humour increases this convergence; and on leaving that lenticular body to enter a less dense medium, they take a new degree of convergence, which is such, that the cone they form behind the crystaline humour has its summit precisely on the bottom of the eye, where it delineates the image of the point from which the rays issued to arrive at the organ. This course of the rays is similar to what we mentioned (642) when explaining the effects of refraction in media terminated by curved surfaces.

The axes of the other two pencils, in entering by the cornea, are refracted, as well as the rays that accompany them: these pencils cross afterwards, on passing through the aperture of the pupil, and undergo, in the crystaline and vitreous humours, further refractions, the effect of which is to bring the rays that compose them nearer to their respective axes, so that they form two new cones, whose bases are on the posterior surface of the crystaline humour, and the summits on the bottom of the eye, where they delineate, as in the preceding case, the images of the points that answer to them in the object.

All the pencils proceeding from the other points of the object act in the same manner, so that a complete image of the object is formed on the bottom of the eye; but an image that is reversed, in consequence of the circumstance that the rays, proceeding from points situated on different sides of the middle point, cross one another, on passing through the pupil. The most common opinion is, that the image is painted on the retina; but there are anatomists of celebrity who have supposed the choroides to be the true canvas of the picture *.

We may verify by experiment what we have said of the cause of vision, by taking the eye of an ox recently killed, and stripping it of its sclerotica behind. If in this state the eye be placed in a hole made in the window-shutter of a dark room, with the cornea outwards, we shall see, in the transparent membranes of the opposite part, distinct images of the exterior objects.

755. This truth once acknowledged, that the instant an object is before the eye, that object has its portrait on the bottom of the organ; it seems as if vision required no further illustration, and we may be led to suppose, that our eyes, when they open for the first time, are already trained, and that the mere presence of objects is sufficient for the impressions made on the

---

* Smith's Treatise on Optics.

retina, and transmitted by the optic nerve to the brain, to enable the mind to represent those objects to itself precisely as they are, and in the places where they are. But we shall conceive something more to be necessary, if we reflect that the image which is painted on the retina is a simple surface figured and coloured, without any reliefs, and is besides the result merely of the action which the extremities of the rays that touch it exert on the organ, and has no connection of itself with the opposite extremities, where the body which is the object of vision is situated. These considerations have led many philosophers to suspect that there existed some intermediary agent, serving to connect the impressions produced by the rays which bodies sent to the eye, with the modifications of those bodies themselves. They imagined the touch to be in some measure instrumental in instructing the eye, and enabling us to rectify the errors into which we were led by this organ, when it was left to itself. But no one has better developed the means which the sense of feeling employs in this business than Condillac *; and it is chiefly from the ideas of this celebrated metaphysician that we shall attempt to explain it.

756. Our first lessons are derived from the various motions which the hand makes, that has its own image in the bottom of the eye. While in turns it approaches nearer to or withdraws farther from this organ, it teaches it to refer to a greater or less distance, to one place rather than to another, the impression that is produced on the retina, from the sentiment we have of every position of the hand, and of the direction and extent of every movement it makes. While one hand passes over the other, it conveys, in a manner, over its surface the colour, of which the

---

* Traité des Sensations.

impression is in the eye; it circumscribes this colour within its limits, and excites in the mind the representation of a body shaped in such a manner. Afterwards when we touch different objects, the hand directs the eye over the several parts of each of them, and renders the arrangement and respective positions sensible to it; it acts incessantly with regard to the eye, by means of the rays of light, as if it held one extremity of a stick, of which the other extremity touched the bottom of the eye, and guided this stick in succession over every part of the object. It seems to inform the eye that the point it touches is the extremity of the ray which strikes that organ; and thus while it runs over the surface of the object, it seems to pronounce its true form. Sometimes uniformly curved on the surface of a globe, the outline of which it follows in every direction, it marks the distinction between light and shade, and gives to what the eye perceives roundness and relief. At other times, obliged to vary its own figure, while it adapts itself alternately to the faces and angular projections of a body, it makes known the various positions and arrangement of the planes that constitute its surface.

When the eyes are once instructed, the experience they have acquired enables them to do without the help of the touch, and the presence alone of objects occasions the return of the same sensations, when the rays proceeding from those objects make similar impressions on the organ.

757. We have said (754), that the image of every object is painted on the bottom of the eye in a reversed situation; and there are men of talents who have inferred from this circumstance, that we naturally see all objects in this state: but we shall readily perceive the little foundation there is for such inference, if we consider, that we see our own body,

which has its image reversed on the retina, like that of other objects; and thus the mere sentiment of our own position determines the sensation which makes us see all objects right.

At the same time that the touch instructs the eye to refer outward the images of objects, and get possession of their forms, it exercises it also in the art of estimating their position in space, their size, and their distance; and when this distance exceeds that to which the motion of the hand extends, we supply the defect by another exercise, which consists in approaching towards the object till we touch it, and then receding from it again; and by the extent of these contrary movements we ascertain its distance nearly. When the object exceeds the compass of our ordinary movements, the proportions we are accustomed to remark serve us as rules by which to apply to more remote objects the impressions that are made upon us; but as the distance increases, circumstances become less favourable to such applications, and beyond a certain limit objects present themselves more or less under a deceitful appearance, and we are led into that kind of errors called *optical illusions*, of which we shall speak hereafter. Let us give a new developement to this interesting subject, and endeavour to follow the eye from the spaces where it is directed by a sort of remembrance of the lessons it has received from the touch, to those vast regions which it leaps over, far, very far from the circuit it traversed with its guide.

758. When we look at an object, there is always some point of it that attracts our notice more particularly than the rest, and towards which the two optic axes are so directed that this point becomes the summit of the angle they form between them. In proportion as an object is nearer or more remote, or,

which amounts to the same thing, as we advance towards it or recede from it, the eyes are continually in motion to vary their figure and position, in such a manner that the two optic axes always coincide with the same point of the object. When the distance is such, that we can measure it by a movement of the hand, or by advancing to touch it, the sentiment we have of the motion which the eyes make at the same time to direct themselves towards the object, gives us the habit of judging of distances from the impressions that are connected with these motions, and of estimating at the same time the position of the object [*]. Hence it is that the hand goes directly to the object that is within its reach, and which it wishes to touch or lay hold of; hence also it is, that with both eyes open we are sure to strike with the end of a stick an object placed within a certain distance: but if we use one eye only to look at the object, the point of union of the two axes no longer existing, it becomes much more difficult to judge of the position of the object, as we may ascertain by the following experiment [†]. Suspend a ring freely to a string on a level with the eye, but in such a manner that you cannot see the hole of the ring. Take a stick about a yard long and fasten another smaller stick crosswise to one end of it. Then shut one eye and try to thread the ring with the small stick, and you will scarcely ever succeed: but use both eyes, and you will do it on the first attempt.

759. It is in consequence of both the optic axes being directed exactly towards that point of the object which we look at in preference, that when we want, relatively to that object, a mere levelling line, as when the sportsman takes aim at the animal he would shoot, we shut one eye to ascertain better in what direction the object is.

---

[*] Mallebranche, Recherche de la Vérité, vol. I, p. 115, and 119.

[†] Muschenbroek, Essai de Phys. vol. II, p. 568, No. 1211.

760. Though every object that is before our eyes has its image in both organs, yet objects are not seen double; because, having previously ascertained, by help of the touch, that such an object was single, at the same time that each optic axis was directed towards it, and its image was painted in the corresponding parts of each retina, we have connected the idea of unity with the sentiment of those impressions, and have accustomed ourselves to identify two sensations, which, so to speak, are in unison with one another. But if the two optic axes no longer concur towards the same point, as when we slightly press one eye sideways with the hand, the object appears double, and it is evident that the two images do not then fall on the corresponding parts of the retinæ *.

761. There is another angle the consideration of which is of importance, in relation to the phenomena of vision. It is formed by the two rays which, on coming from the extremities of the object, cross one another in the pupil. This angle is called the *visual angle.*

Behind this a second angle is formed, by the same rays passing through the crystaline and other humours of the eye. This angle subtends the diameter of the image on the bottom of the eye, and it is obvious that it increases and diminishes with the first angle; and when these angles are small, their increase and decrease, as well as the increase and decrease of the diameter of the image, are apparently in the inverse ratio of the distances of the object from the eye.

---

* A similar illusion may be produced, that has its origin in the touch. If we pass the middle finger over the forefinger, so as to make this last turn towards the thumb, and we then place a small globular body under the tips of these fingers, and press it, that it may be more exactly in contact with them, we shall imagine we feel two globes. In this case, the finger that is placed out of its natural position exerts an action, which, no longer in accord with the other finger, gives rise to a sensation that seems to refer to a new object. In this experiment the fingers may in a manner be said to squint.

Now the magnitude of an object may be understood in several different relations. The true dimensions of an object, considered in itself, give what is called its *real* or *absolute magnitude*, and the opening of the visual angle determines the *apparent magnitude:* from which we see that, the real magnitude being a constant quantity, the apparent magnitude varies continually with the distance, real or imaginary.

762. If we always judged of the dimensions of an object from its apparent magnitude, every thing around us would be continually undergoing in this respect very sensible variations, which would lead us into strange mistakes. For example, a giant twenty-four decimetres (or 8 feet) in height, seen at the distance of four metres, would not appear taller than a dwarf of six decimetres (or 2 feet) seen at the distance of one metre; for both would be seen nearly under the same angle.

But the experiments we have made on the comparison of distances with magnitudes by the help of touch, have enabled us to correct our ideas, in circumstances respecting which it is of the greatest importance to us that we should avoid mistakes, that is, in those which relate to objects that are near us: for then the distance, of which we judge with sufficient accuracy, is in our estimation ascertained, and we are prevented from being imposed upon by the erroneous notion that might result from the single consideration of magnitude.

Thus the different positions of the eyes, answering to the variation of the angles formed by the optic axes, in proportion as the objects become nearer or more remote, reproduce in us the impression of the distance, such as the touch has taught us to estimate it; and this impression combines itself with that of the apparent magnitude, or the extent which the image occupies on the bottom of the organ, so that the sensation which represents to us the real magnitude is as the product of these two elements. For example, if a giant twenty-four decimetres in height, who at first was at the distance of two metres, should remove to a distance of four metres, on one hand his image on the bottom of the eyes is diminished by half, but on the other, the distance becomes doubled; and the sort of combination that takes place in us of the two impressions, one relative to the magnitude, and the other to the distance, answering to each position of the giant, is equivalent, if we may so express ourselves, to the constant product of two quantities, of which one increases in proportion as the other diminishes: whence it follows, that the giant always appears to us of the same height.

We infer also from what has been said, that when two unequal objects are placed at the same distance, we judge of their respective magnitudes from the proportion between the visual angle appertaining to each, or between the magnitude of their images on the bottom of the eye: for then the two products that result from the impression of the distance combined with that of the magnitude, are a common quantity, videlicet, the first impression, for which we may substitute unity; and thus they are proportional to the other quantity, which is the impression of the magnitude.

763. As long as the objects are sufficiently near to us for the angles formed by the two optic axes to have a perceptible measure enabling us to compare them, so long will the motion of our eyes, respecting

these angles, assist us in representing to ourselves, with a degree of accuracy, the distances, and at the same time the magnitudes, whose estimation depends in part on that of the distances; but when the remoteness of the objects renders these angles so small that they escape comparison, the adjudged magnitudes depend in great measure upon the apparent magnitudes: and thus an object situated at a considerable distance appears to us much smaller than it really is.

764. We also judge objects to be nearer or farther off accordingly as they are more or less clear, and our perception of them is more or less definite and distinct. It is in conformity to this and the preceding principle, that painters diminish the size of their figures in proportion as the objects they represent are supposed to be at a greater distance, and that they give to the outlines very faint tints, or even sketch these outlines so lightly that they are lost in the colour of the ground of the picture, when the distance is very considerable.

765. Lastly, when between us and an object several other objects intervene, this new circumstance assists us still further in estimating the distance of the first object, by a sort of addition which we make of all the distances of the intermediate objects, to form of them a total distance: from which it follows, that the object in this case appears to be farther off than it would if the intervening space were unoccupied, and furnished us with no rallying point from which to compute the divisions of the distance.

766. To confirm what we have said upon the subject of vision, we shall add an example or two that prove to what degree the eye is deficient in the art of seeing, when it admits light for the first time. A youth of thirteen years, on whom Mr. Cheselden had

performed the operation for the cataract [*], was at first so far from being able to judge of distances, that he supposed all objects alike to touch his eyes (these are his words) as the things which he felt touched his skin. The objects most pleasant to him were those of a smooth surface and a regular form, though as yet he was unable to judge of form, nor could he tell why he preferred these objects to others. It was upwards of two months before he could perceive that pictures represented solid bodies: he had before considered them as planes differently coloured; and when he first began to distinguish the reliefs of the figures, he expected, on touching the canvas, to find in reality solid bodies, and was greatly surprised on passing his hand over the parts, which, by the distribution of light and shade, appeared round and uneven, to find them plane and smooth like the rest. He asked which of his senses deceived him, was it his sight or his feeling? He was shewn a miniature picture of his father that was painted on the case of his mother's watch, and he said, that he perceived the representation of his father; but he asked, with the utmost astonishment, how it was possible for so large a visage to be contained in so small a space? which appeared as impossible to him as for a pint to hold a hogshead [†].

The same operation performed by Mr. Grant on a blind man of the age of twenty, was followed by similar circumstances. When the eyes of this youth were first struck with the rays of light, his whole person exhibited the most extraordinary ecstasy. The operator was before him with his instruments in his hand: the youth examined him from head to foot, and seemed to compare his own figure with that before his eyes; every thing appeared to him similar except the hands, for he took the surgeon's instruments for parts of the hand. He wished to walk, and seemed terrified at every thing around him. He could not reconcile the sensations he experienced from sight, with those which the same objects had produced on him by feeling; and it was only by degrees that he was able at length to distinguish and understand forms, colours, and distances * (*c*).

---

[*] The cataract is a privation of sight occasioned by the opacity of the crystaline; and the remedy is to displace the crystaline either by depressing or by extracting it.

[†] Philosophical Transactions, No. 402, vol. XXXV.

---

* Gazette Littéraire de l'Europe, 21st of March, 1764.

(c) Mr. Ware, in December 1800, restored sight to a boy about eight years old, who had been blind from the age of a year, by puncture of the capsule of the crystaline. This eminent oculist remarks, that, contrary to the experience of Mr. Cheselden's patient, who is stated "to have been so far from making any judgment of distance, that he thought all objects touched his eyes, as what he felt did his skin," this young gentleman distinguished, as soon as he was able to see, a table a yard and a half from him; and proved that he had some accuracy in his idea of distance, by saying that it was a little farther off than his hand could reach. Nor was this the only particular in which this youth differed from Mr. Cheselden's patient, who,

Optical Illusions.

767. We have already had occasion to mention the mistakes into which we are led by our eyes, when the objects are out of the circle of our ordinary observation; and we have seen in this case, that we deceive ourselves equally both as to magnitude and distance. Another cause that helps to impose upon us, is the diversity of positions which bodies assume with regard to us, arising either from the motions by which they are transported in space, or from those which we make ourselves. The circumstances which determine these errors, to which the name of *optical illusions* have been given, are extremely various; the sphere that embraces them is immense; they extend even to those vast bodies that revolve in the celestial regions, and the hypothesis relative to their influence on the manner in which many of the planetary phenomena exhibit themselves to our observation, is become the foundation of a theory that reduces these phenomena to a happy simplicity, which were before so embarrassing to persons desirous of seeing realities in their simple and genuine appearance. We shall explain some of these illusions, selected from such as are most familiar to us, or best entitled to notice.

768. There is no person probably who, standing at one of the extremities of a long avenue, has not observed that the two rows of trees of which it is formed

---

points involved in doubt. The reader who wishes to acquaint himself with the leading principles of the different hypotheses, should peruse, in addition to what is here given by M. Haüy, *Berkeley's Essay towards a New Theory of Vision*,—*Wells's Essay on Single Vision*,—*Jurin's Essay on Vision*, at the end of *Smith's Optics*,—*Robins's Remarks on this Essay*, in vol. II. of his *Tracts*, and the article Vision in *Hutton's Dictionary*, where there is an abstract of the theories of *Porterfield*, *Young*, and *Hosack*.—Tr.

appear to converge towards each other, so as even to touch, if the avenue be of sufficient length. In this case the intervals between the corresponding trees on each side subtend visual angles that regularly diminish, till at last they are insensible at a great distance. It follows from this, that in the small picture on the bottom of the eye, the images of the trees are situated on two lines that are inclined towards each other, and tend towards a common point; or, which amounts to the same, the intervals between the images of the corresponding trees diminish gradually, in such manner that the last interval is almost nothing. Now, if we suppose that the two optic axes direct themselves successively towards the different trees as they increase in distance, the variation of these angles, and at the same time that of the impression of the distance, will continually become less perceptible; and, by a necessary consequence, the impression of the magnitude, which depends here on the interval between the corresponding trees, will be so predominant, that it will nearly determine of itself the type of the sensation; so that two lines exactly parallel will present themselves to us under the aspect of two converging lines. It is owing to a similar cause that, when we are at the entrance of a long gallery, the ceiling appears to slope downwards a little and the floor to rise.

769. If it be a single plane only that is situated with respect to the eye like one of the planes in the preceding instance, as when we are at one end of a long piece of water, that plane will also appear to rise, more and more in proportion as the parts shall be remote from the spectator; for in this case he compares the plane with the line of the horizontal level, which passes through the eye and performs the office of a second plane, towards which the first seems to

approach in consequence of the diminution of the visual angles that proceed from the corresponding points of each.

770. If the spectator at the foot of a lofty tower looks to the summit, the tower, on the side on which he stands, will appear to incline; for he compares its position with a vertical line that passed through the eye; and accordingly this vertical and the height of the tower are two parallels that should tend in appearance to meet at the summit (*d*). In these cases the vertical line and the horizontal line are kinds of ideal limits to which the eye refers the visual angles, one of the sides of which is always one or other of these lines; in like manner nearly as, when we would estimate with the eye the inclination of a line existing in space, we compare it with an imaginary horizontal or vertical line that passes through one of the extremities of that line.

771. When we are stationed at a certain distance from a rising ground, it appears to us longer than it would if it were on a level with the horizon; which is evident from the mere inspection of *figure* 114, where *m n* represents the inclined position of the ground, and its length, *m n'*, what it would be if it were horizontal, and *n o m*, *n' o m*, the visual angles answering to the two positions.

772. From the same principles, we shall be able to explain a multitude of other optical illusions, that

---

(*d*) There is another source of illusion with regard to vertical objects. In looking upwards, after inclining our heads all we can, we are apt to imagine that we have brought the axes of our eyes to point towards the zenith; but instead of this being the case, our eyes even then look forward many degrees from that point, so that whatever is in or near the zenith seems to hang over as many degrees behind us. And this accounts for the greater part of the mistakes that people generally are apt to be under, concerning the altitudes of stars having very high elevations.—Tr.

must daily present themselves to the most inattentive observer. For example, if we are situated opposite the middle of a long line that is very remote from us, we shall observe it to inflect both to the right and left, so as to appear part of a curve, of which the axis passes through the eye. If we stand before a regular polygon of a certain extent, the sides that are parallel to the surface of our body will look larger than those which are oblique, and the polygon will have an irregular appearance. This observation may easily be made, and we may vary the circumstances at pleasure, by placing ourselves in different stations near the great basin of the Tuileries.

773. What we have said leads us to some considerations upon the subject of perspective. The object of this science is to represent on a plane bodies of every form. Now, if, for greater simplicity, we suppose the body of which we would trace the image to be terminated by plane faces, the figures of these faces will necessarily differ from what they are on the body itself. If, for example, we would represent a cube, we shall be very well able to give the figure of a square to one of the faces of the image; but the two adjoining faces, which concur with the first in the formation of one and the same solid angle, will be evidently quadrilaterals of a different figure, since the sum of the three plane angles in question, considered in the image, ought to be equivalent to four right angles, whereas they are only equal to three on the solid. Notwithstanding this difference, we fail not to succeed by a certain arrangement of lines which constitute a sort of illusion, and exhibit to the eye a faithful portrait of the original object.

To understand the reason of this illusion, let us suppose a cube to be situated in space, in a given position relatively to the eye of the spectator, and let us also suppose it to be transparent. From what we have said of the manner in which vision is effected, it results that the axes of the different pencils of light transmitted from the different points of the cube, and which are the only lines we have occasion for here, after crossing one another in the aperture of the pupil, will form a kind of small pyramid, whose base will rest on the bottom of the eye, where it will produce the image of the cube. Now, let us suppose a plane, or transparent picture, parallel to the bottom of the eye, and through which all the axes pass that proceed from the different points of the cube to this eye, each leaving its impression there. The image formed by the whole of these impressions will be similar to that which will be painted at the bottom of the eye, allowance being made for the slight difference that must be occasioned by the curvature of this organ. Lastly, let us imagine the picture to become opaque, and that the image of the cube still exists in it; that which was at the bottom of the eye will be still the same, and its immediate object will be the first image, all the points of which will send to the eye rays situated precisely like those which came from the cube. Now such image is what is called the *perspective of the cube.* ..From this statement we conceive how the image, the traits of which are the same at the bottom of the eye as those which would be formed there by the rays proceeding from the different points of the cube, must represent this cube as faithfully as the level of the plane which serves as canvas to the picture would permit. Geometry furnishes rules for tracing the lines that form as it were the sketch of these kinds of portraits; and when to this sketch, which possesses in itself a striking resemblance, the art of painting adds the distinction of light and shade, and the magic of colouring, there results from the whole an illusion that is nearly perfect, and that wants only a little management of the eye to excite all the pleasure of surprise.

774. One of the most remarkable optical illusions is that which leads us to suppose the moon to be larger when it rises, than it is when at a certain height above the horizon. We must all have frequently been struck with the contrast which the diameter of this luminary exhibits, when compared with itself in the two situations we have mentioned. To understand the cause of this we must reason from the principle that we see the sky in the form of a very depressed vault, much less than a hemisphere. Let T (fig. 113) be the half of the terrestrial globe elevated above the horizon *u x*; *u y t x* half the circle through which the moon passes in its diurnal motion, and *a c g b* the corresponding half of the curve which bounds the sensible part of the hemisphere *. The different strata of which the atmosphere is composed, reflect in preference the blue rays of the light of the sun, and they are the rays passing to the eye that occasion the medium to appear to us of that colour. The surface *a c g b*, which represents the limit to which all these reflections extend, thus appears to our eyes like a vault, to which all the stars seem to be attached. Let us suppose a spectator placed at the point *o*, and let us draw from this point a plane, *p o i*, parallel to *u x*. The spectator, to whom the curvature of the earth is imperceptible, will be circumstanced precisely as if this plane really existed,

---

* For greater facility of elucidation, we have represented the atmosphere as more extensive than it really is; but the true state of things is in favour of the explanation.

and thus the celestial vault will be reduced in his estimation to the arch *d c g e*, which rests on the same plane; from which it follows, that the extreme points, *d*, *e*, of this vault will be seen by him at a much greater distance than the culminating point *l*.

On the other hand, the objects that are interposed between us and the moon, when this luminary is at the horizon, contribute still further to increase the apparent distance of the points, *d*, *e*, with regard to the spectator (764 and 765), and to diminish the curvature that he ascribes to the celestial vault.

Let us suppose *f l h* to be a section of this vault, such as it appears to us from the double effect we have mentioned. The arches *p ú*, *i x*, being deemed infinitely small, on account of the great distance of the moon from us, the instant its centre arrives at *n* may be considered, without palpable error, as that of its rising. The spectator then sees it under the angle *p o r*, and refers it to L, at the distance *o f*. When the moon is afterwards arrived at *z*, that is, at the meridian, the spectator sees it still under the same angle, $p' o r'$, but refers it to *l*, that is, to a point that is much nearer to him; accordingly, though the image of the moon always occupies the same space in the eye of the spectator, yet as that luminary appears to be at a smaller distance, he judges it to be smaller, in the proportion nearly of *o l* to *o f*; for then the two products that result from the impression of the magnitude combined with that of the distance (762) having a common quantity, which is the first impression, are in some sort proportional to the second; and thus we form an idea of the real magnitude from the proportion between the apparent distances.

Mallebranche, to whom in great measure we are indebted for this explanation, has verified it by an experiment both simple in itself and easily made, which is by looking at the moon in the horizon through a piece of smoked glass. In this case it appears no larger than when at its meridian height, if the glass be placed so near to the eye as completely to eclipse all other objects and afford no opportunity of estimating distances * (*e*).

775. We shall now proceed to optical illusions that have their source in motion. Let us conceive first an immoveable object, and a spectator who moves, from the left to the right, for example, but in such a manner that he is not conscious of it. The object in this case being continually more to the left with regard to the spectator, his eye will receive the same impression as it would have done, if, immoveable himself, he had seen motion communicated to the object from the right to the left. In general, when we move without perceiving it, we refer such motion in a contrary sense to the objects about us. Thus, when we are at rest in a boat that is in motion, we see the trees, buildings, and other objects, approach, pass before us, and remove to a distance, accordingly as the boat is

---

* Recherche de la Vérité, vol. I, p. 127, et seq. and vol. III, p. 159, et seq.

(*e*) The sun undergoes a similar augmentation in its apparent diameter when near the horizon, and for a similar reason: this circumstance may perhaps have suggested to the poets in their personifications of this luminary, the propriety of saying, that *he rises like a giant.*

The above explication of the phenomena of the horizontal sun and moon, is stated preferably to the nearly analogous one given in Smith's Optics: for though both authors seek for the source of the illusion in the apparent flatness of the sky, yet M. Haüy is far the most successful in tracing the supposed cause of that flatness, and in connecting one appearance with the other. Dr. Okely has lately given an explanation much like Haüy's (see *Phil. Journal,* No. 53, N. S.); but probably without being at all aware of the coincidence.—Tr.

rowed in opposite directions. A celebrated poet has expressed this sensation in a very picturesque manner when he makes the navigator say, on setting sail,

Provehimur portu; terræque urbesque recedunt *.

776. Let us suppose that a spectator, believing himself at rest, moves to a certain extent represented by A B (fig. 115, pl. XVIII), while an object at a certain distance passes over *a b*. In this hypothesis, A*f* will be the visual ray in the direction of which the spectator will see the object when he begins to move, and B *d* that of the direction in which he will see it when he stops. Then if the relative positions and the respective length of the lines A B, *a b*, are such, that the two visual rays intersect in some point, *c*, the object will appear to the spectator to have moved from the left to the right, or from *f* towards *d*, that is, in a direction the reverse of the motion that has really taken place according to *a b*.

To render this explanation plainer, let us suppose that at the commencement of the motion the spectator looked at the object when at *a*, through a telescope in the direction A *a*; in this same position he keeps the telescope during the rest of the motion, so that when the object is arrived at *b*, the glass has the direction, B *n*, parallel to the line A *a*. Then, to see the object anew the spectator is obliged to place the telescope in the position B *b*, that is, to make it turn from left to right, which leads him to imagine that the object has moved in the same way.

777. Let us now conceive that the spectator moves through A B (fig. 116) while the object passes through *a b*, in the reverse direction of A B. If the spectator were stationary, the visual rays belonging to the two

---

* Virgil, Æneid, book iii, verse 72.

extreme terms of the motion of the object would be A *af* and A *b r*, so that the spectator would judge of the magnitude of this motion by the opening of the angle *b* A *a*; but as he has himself moved through A B, the two visual rays will be A *f* and B *d*, and the angle by which the spectator will estimate the extent of the motion will be *d c f*, or its equal A *c* B, greater than the angle *b* A *c*, that would have obtained had the spectator remained stationary, since it is equal to the sum of the angles *b* A *c* + A *b c*. The spectator therefore will deem the motion of the object to be more rapid than it really is, because by ascribing to it his own motion along A B, according to a direction, B A, which is the same as that of the motion of the object, he will ascribe to it a velocity that does not belong to it. If the spectator were to employ here also a telescope to look at the object, this telescope at first directed in the line A *f*, having at the end of the motion a position according to B *n*, parallel to A *f*, would describe, in turning, the angle *n* B *d*, considerably larger than the angle that would have been formed had the spectator continued at rest.

778. Lastly, let us suppose that the motion, A B, of the spectator (fig. 117) and the motion, *a b*, of the object are not contrary to each other; and that the directions of the lines they describe are so combined with the periods of time employed in forming those lines, that the visual rays A *a*, B *b*, belonging to the two extreme terms of the motion, and all the rest which relate to the intermediate points, are invariably parallel to one another: then the object will appear at rest to the spectator, who imagines himself to be at rest, and we readily perceive that he will constantly see the object at the end of a telescope that should remain in a uniform position during the whole experiment.

The hypothesis of a spectator, when in motion himself without being conscious of it, ascribing the motion in a contrary sense to objects that are at rest, has enabled us to explain the apparent diurnal motion of the sun, in consequence of the real motion of the earth round its axis; and upon the same principle we may account for the annual motion which the sun appears to have in the ecliptic; while the other hypotheses, relative to the simultaneous motion of the spectator and some object before his eyes, have furnished the true cause of the seeming irregularities in the periodical revolutions of the planets, accordingly as they are thought to take a retrograde course in their orbits, or to move with increased velocity, or to remain stationary for a time.

779. When, while we are running, we look at an object that is at a great distance and has no motion, or none but what is imperceptible to us, it seems as if the object ran with us and in the same direction; as, for example, when in running we look at the moon. The visual ray, constantly directed towards that luminary, forms with it in this case, on account of the immense distance, such small angles, in proportion as it changes its direction, that the directions are to the senses parallel to one another, so that the moon appears to move at the extremity of that ray; and as we have the sentiment of the motion which the eye makes, from which the same ray proceeds, we ascribe a similar motion to the moon (*f*).

(*f*) The curious phenomenon of *accidental colours*, first attended to by Buffon, deserves some mention under the head of optical illusions. The phenomenon is this: If a person look stedfastly and for a considerable time at a small *red* square painted upon *white* paper, he will at last observe a kind of green coloured border surround the red square. If he now turn his eyes to some other part of the paper, he will see an imaginary square of a delicate green bordering on blue, and corresponding exactly in point of

We have said (626) that the progressive motion of light, combined with that of the earth in its orbit, had furnished the explanation of the phenomenon called the *aberration of the stars*. This explanation, which reduces the phenomenon to a simple optical illusion, naturally offers itself here.

780. There have been observed in the fixed stars slight motions, which some philosophers had been led to regard as an appearance produced solely by the earth's motion in its orbit. Let us choose the most simple case, which must be that where the star which we take for an example, shall be situated at the pole of the ecliptic, and let us suppose the conjecture of the astronomers we have just mentioned to have some foundation. On this hypothesis, in which the observer will ascribe to the star his own insensible motion, it is clear that his different visual rays, directed constantly towards the star, will form a cone, of which the base will be the ecliptic and the summit will coincide with the star. The same rays prolonged will form above the star a second cone opposed to the

size with the red square. This imaginary square continues visible for some time, and indeed does not disappear till the eye has viewed successively a number of new objects. To this imaginary square the name of *accidental colour* has been given. If the square be *yellow*, the accidental colour is blue; the accidental colour of green is red; of blue, yellow; of white, black; while on the contrary, that of black is white. And in general, the accidental colour is the colour resulting from the mixture of all the rays of light, those rays excepted which are the same with the primitive colour.

The theory of accidental colours was considered by Buffon in the Memoirs of the French Academy for 1743; also by Dr. Darwin and some other philosophers: but the most satisfactory explanation we have seen, is that by Professor Scherffer, of Vienna, published in the *Journal de Physique*, and an abstract of it under the article COLOURS in the *Supplement to the Encyclopædia Britannica.*

For an elucidation of the probable causes of many other optical illusions, the reader may consult the valuable treatises of optics by *Harris* and *Bouguer*.—TR.

first by its summit; and the spectator referring the star continually to the direction of these prolongations, will imagine that he sees it describe a small circle in the heavens, in such manner that the star will always appear to him in the point of the circle diametrically opposite to the point of the ecliptic which he will occupy himself.

But the fixed stars are at so great a distance from the earth, that the angle formed by the visual rays, which, proceeding from the two extremities of the diameter of the ecliptic, pass in their course through one of these stars, and which is called the *angle of the annual parallax,* is so extremely small that it cannot be appreciated, and no sensible appearance of motion therefore can accrue to the star from this cause. The phenomenon also, as furnished by repeated observations, is totally different; for the star, instead of appearing in the part of its annual circle opposite to that of the ecliptic in which the observer is, is 90 degrees on this side of it, and is thus always so far behindhand with respect to the motion it would have by virtue of the parallax. Besides, the angle formed by the visual ray directed towards the star, with the line that passes through the centre of the circle in which is the real position of the star, is 20″; whence it follows, that the diameter of the circle which it appears to describe in the course of a year is 40″.

781. Dr. Bradley, who had observed with great assiduity all the circumstances of this apparent motion of the fixed stars, discovered at last the true explanation of the phenomenon; and the idea which suggested it to him was one of those happy strokes of genius that constitute an epoch in the history of the sciences. But before we proceed to the explanation, let us establish the principle on which it is founded.

Let us suppose that a ray of light, in proceeding from the radiant point *a* (fig. 118), strikes an eye situated at *m*, in a direction *a m*, and with a velocity represented by that line; let us suppose further, that at the moment the eye is struck by that ray it is itself moving in a direction *m f*; and let us represent by *m n* the space which it passes through in every instant of time, equal to that which the ray employs in passing through *a m*. The eye receiving at *m* the ray *a m*, will itself strike it with the force of its own velocity measured by *m n*; and we shall conceive, by a little attention, that this apparent impression would also take place on the supposition of the ray being immoveable in space. But, on the other part, the eye really receives the impression of the motion which the ray had in the direction *a m*; whence it follows, that if we complete the parallelogram *m n d a*, the two impressions will be confounded in such a manner that the eye will be in the same case as if the ray of light had struck it in the direction of the diagonal *d m*. From which we conclude, that the eye will see the radiant point *a* in this same direction.

It results from what we have said, that if the vemotion is to make us see the stars where they are not, and to produce those appearances so happily explained by Dr. Bradley.

782. Let *a* (fig. 119) be the true place of a fixed star, which we still suppose to be situated at the pole of the ecliptic; let *t n z m* be the circumference of the circle, and *n* the station of the spectator. While the eye of the spectator is struck by a ray, *a n*, issuing from the star, it strikes it itself, in such a manner that with regard to the spectator the impression is transformed into that which he would receive if his eye were struck in the direction *r n*, coinciding with the tangent at the point *n*. Let us conceive *a n* and *n r* to have the same proportion between them as exists between the velocity of light and that of the earth in its orbit, and let us complete the parallelogram *a n r c*. From what we have said but just now, the eye will refer the star to the direction of the diagonal *n c*. Now the velocity of light is to that of the earth in its orbit as 10313 is to unit; and if we calculate from these data the value of the angle *a n c* we shall find it to be 20″, conformably to observation.

Now if the motion of the star could be the effect of the parallax, the spectator placed at *n* would refer the star to the direction of the line *n a*; from which it follows, that he would see it at the point which answers to *d*, on the corresponding diameter of the small annual circle which the star would appear to describe in the heavens: but he sees it, on the contrary, at the extremity, *c*, of the diameter which cuts the preceding one at right angles. The same effect will be repeated during the whole motion of the spectator in the ecliptic; and thus the star in running through its circle of aberration, *g c d b*, is always, as we observed before, 90 degrees behind, with respect to the position it would have, if the annual parallax were the cause of it apparent deviations.

We have reduced the phenomenon to the simplest case, namely, that in which the star being situated at the pole of the ecliptic, all the rays which it sends to the spectator are perpendicular to the route of the eye; so that the star appears to describe a circle, because the difference between the two diameters of the ellipsis that represents the earth's orbit may here be neglected: then, the measure of the aberration is constantly 20″. The apparent motions of other stars which have different positions produce ellipses more or less elongated, in each of which the quantity of aberration increases and diminishes alternately, in proportion as the star approaches the extremities of the large or small axis of its ellipsis.

The explanation which Dr. Bradley has given of the phenomenon we have been considering, at the same time that it confirms the discovery of the progressive motion of light, adds to the proofs we possessed before of the earth's motion round the sun; and it is thus that truths derive new force from results that shew them to us as forming so many links in the ing with objects of all dimensions, of every form and every colour. In an indivisible instant the scene is conveyed to the bottom of the eye, on a space incomparably smaller than any one alone of the objects it embraces; and the rays which, as messengers in this business, hasten from all the objects, nay more, from all the points of every object, pass, seemingly in confused crowds, through the aperture, much smaller still, of the pupil, without their harmony being at all deranged. The eye, in its turn, without any confusion, seizes on this immense whole, of which the minutest details form each a whole; it separates or groupes them at its pleasure; and while the ear, struck by too many voices at once, hears nothing but noise, the eye, amid the diversity of languages in which so many objects seem to address it, understands the meaning of each; nor is this sort of commerce disturbed even by the contrast which the motion of some, forms with the stillness of others. Let the eye change its position; let it look to another quarter: a new scene instantly arises, a new concourse of various impressions, still, as in the preceding instance, clear and distinct: every thing extraneous relatively to the eye is changed; but the eye itself is invariably the same.

Such is the organ of sight, when, alone, without any adscititious aid, it exerts its natural faculties. We have now to examine what the arts have done to extend still farther its power and procure it new modes of seeing.

Effects of regularly reflected Light on Vision.

We have explained (725, et seq.) in what manner the rays of light reflected by the more or less uneven surfaces of ordinary objects, enable us to perceive the forms and colours of those objects. But when the reflection takes place regularly on the surface of polished bodies, to which the name of *mirrors* has been given, the rays sent from such surfaces are directed towards our eyes as if they came from the different points of an imaginary object, that presents itself to the organ with all the features of reality. We shall examine in order the properties possessed by plane mirrors, by convex mirrors, and by concave mirrors.

Plane Mirrors.

784. If we suppose a radiant point situated opposite to a plane mirror, we evidently perceive, in the first place, that this point sends from all its parts divergent rays to the surface of the mirror. Now let us imagine an eye to be situated before this same mirror; among the rays reflected in an infinity of different directions, there will be a certain number that will be directed towards the aperture of the pupil through which they will pass, and we may consider the whole they will form as a truncated cone, of

the rays have at the instant of their arrival; every thing else takes place without its being conscious of it: and because it is in the habit of referring the objects to some point of the direct line in which the rays strike it, it will see, at the imaginary summit of the cone which has entered the pupil, an image of the radiant point, which will produce in it the same illusion as if this point had been suddenly conveyed behind the mirror.

It is besides easy to conceive that the image will be placed at the same distance beyond the mirror as the object is on this side of it, since the imaginary cone, which terminates at this image, is equal and similar to the real cone which comes from the object, and forms the same angle with the surface of the mirror.

We shall enter more completely into this explanation by the help of fig. 120, where A B represents a line taken on the surface of a plane mirror, R the radiant point, *s* R *t* the cone of rays which, after being reflected at *s t*, proceeds towards the eye placed at O, and causes it to see the image of the radiant point in the place, *r*, of the imaginary junction of the rays *m s*, *n t*, and of all the intermediate rays.

785. Instead of a simple radiant point, let us place before the mirror an object that has extent of three dimensions; the results of the reflected light will still be the same as those of the direct light, that is, the eye will see behind the mirror an image equal and similar to the object, and so situated, that all the corresponding points of both will be at the same distance on this side and the other of the mirror.

786. We may easily judge that the gestures we may make before a mirror are repeated in a contrary way by the image; and on this account, when we would perform, by the assistance of the mirror, motions which require that we should see ourselves, some

previous practice is necessary, to avoid the errors into which this deceitful imitation would lead us.

787. We can see in a mirror but a part of ourselves, the height of which will be double that of the mirror: for the height of the image represents the base of a triangle, the sides of which are those of the visual angle that subtends that height; and, in the same case, the height of the mirror represents a line that cuts the triangle in a direction parallel to its base. Now this line divides each visual ray into two equal parts, since the mirror is equally distant from the image and the eye; whence it follows, that this line is equal to half the base of the triangle. Therefore the height of the mirror is also half the height of the image, and at the same time of the part of our body, which this image represents in its natural size.

788. The distance of the eye from the mirror and the height of the mirror and the object being given, we may easily ascertain at what distance from the mirror an object must be placed that it may be completely seen there in a position parallel to that of the mirror; for, supposing the thing done, and the construction to be the same as that above (787), we shall

which is equal to the distance of the eye from the mirror, *plus* that of the mirror from the image; from which it follows, that by retrenching from the fourth term the distance of the eye from the mirror, which is given, we shall have the distance of the mirror from the image, the same as that of the object from the mirror. For example, if the height of the mirror is 1·6 metre and that of the object, 2·4 metres, and the distance between the eye and the mirror is 4 metres, we shall have 6 metres for the distance of the eye from the image, from which having deducted 4 metres the distance of the eye from the mirror, we shall have 2 metres for the distance at which the object must be placed from the mirror to be seen in it completely.

789. When the object moves before the mirror, by advancing towards or receding from it, the image behind the mirror performs in its movements the same journey as the object; but if the mirror approach towards or recede from the object, the image performs a journey as far again as the object. Let us suppose, for example, the mirror to recede a metre from the object; if the image only receded in the same degree, its distance with respect to the mirror would be the same as before the motion, and would thus be a metre less than that of the object. The image therefore must move two metres for the distance on each side to continue equal.

790. It results from what we have just said, that if the object be in a vertical position and the mirror inclined 45° to the horizon, the position of the image will become horizontal, since it would be necessary that each point of the height of this image, which was at first situated vertically, should have described an arch of 90°, which cannot take place without the image appearing parallel to the horizon.

791. We see by this, why the motions of images

represented in water are much more perceptible than the agitations of the liquid. These sorts of images are besides always fainter and as it were sketched only, because they are merely produced by the reflection of the rays that escape the refractive power of the water (647). This partial reflection takes place equally in glass mirrors; and hence it is that such mirrors give two images of every object, of which one is produced by the rays which reflect themselves at the front surface of the glass, and the other by the rays which, having penetrated the thickness of the glass, reflect themselves on contact with the posterior surface and the metallic substance with which it is coated. This second image is much stronger than the other, and is the only one in ordinary cases that attracts attention: but if we present the head of a pin to the glass, so as nearly to touch it, and give to the visual ray a certain degree of obliquity, we shall plainly perceive the image reflected by the front surface of the glass, and it will have an inclination that will cause it to be seen more distinctly than that which is occasioned by the back surface.

792. If we employ in this experiment a lighted

(ibid.), being repelled in the direction *e k*, is lost in regard to the eye. The part *e m*, after being reflected on contact with the glass and the amalgam, arrives at the point *u*, and if the two surfaces of the mirror were perfectly parallel, this part would be wholly found in a fit of easy transmission (735); but as we cannot suppose the parallelism to be exact in all the corresponding points of the two surfaces of the mirror, it will suffice for our experiment, that there shall be, in the small space situated round *u*, and on which the stream of rays, *m u*, falls, some points that give a unit of interval, greater or less, that one portion of the same rays may be reflected anew according to *u y*, while the other portion, after being refracted in the air, shall proceed in the direction *u o*, and shall enable the eye to see an image of the radiant point, situated in the direction *o u*. A second beam, *r x*, subdivides itself in the same manner, at the point *x*, into two parts, of which one, *x z*, penetrates the glass, and the other, *x o*, which is reflected at the interior surface, proceeds to meet the eye, and causes it to see a second image of the radiant point situated in the direction *o x*, and which is fainter than the first when the rays which convey the impression of it to the eye form with the surface of the mirror an angle rather large, because in this case the number of such as undergo refraction is much greater than the number of those which escape it. The two images which we observe when we place a pin near the glass, are analogous to those we have been speaking of; but a third pencil follows the course *r a g l t n o*, in such manner that every time it meets the anterior surface of the glass, it is subdivided, like the preceding ones, into two parts, one of which is refracted and the other reflected; and its position is such here, that after having experienced two reflections at *g* and *t*, on contact with the glass

and the quicksilver, it reaches the eye, and occasions it to see a third image, situated in the direction *on*, and less perceptible than the other two.

By considering the figure attentively, we shall form an idea of the partial refractions and reflections which take place at the different points of the immersion of the rays proceeding from the radiant point. We shall conceive that there must be other pencils, which, after having experienced in the interior of the glass, three reflections, four refractions, &c. will paint on the bottom of the eye new images of the radiant point, such as will regularly become fainter, in proportion as the reflections and refractions that fail to concur in the effect shall successively take from the different pencils a greater portion of the rays that originally composed them. Now since accordingly as the rays shall have more windings to make between the two surfaces of the glass, their incidence must necessarily take place at the points *e*, *a*, &c. always situated more behind, with respect to the eye, and their emergence be at the points *u*, *n*, situated more in front, their inclination on the glass will diminish in proportion, and each partial pencil of account at the same time of the augmentation of the distance.

Concave Mirrors.

794. The concave mirror, which is now to occupy our attention, produces very singular effects, some of which appear like the tricks of a juggler. In a certain point of view, the image appears direct and situated behind the mirror, but very much amplified, and at the same time more remote from it, than the object is in front. Remove this object by degrees farther from the mirror, and the image first disappears, or presents only a confused assemblage of light and colours; but all at once, at a greater distance, the image resuming its form, becomes reversed, and, as if it proceeded from the mirror, advances towards the spectator; then, according to the motions which the object makes, the image touches it or stations itself by its side, so that we might suppose the object itself to have doubled its existence.

795. To explain these different effects, let us conceive *b n m* (fig. 122) to represent a portion of the circumference of one of the great circles of a concave spherical mirror, and that R is a radiant point situated in the plane of that circle: all the incident rays, R*d*, R*h*, R*f*, &c. which must be supposed infinitely near to one another, will be reflected on the side of the axis R *n*, in such a manner that the reflected rays will intersect each other; for instance, *d r* and *h t* at the point *r*, *h t* and *f g* at the point *t*, and *f g* and *o g* at the point *g*, situated on the axis. Now, in proportion as the incident rays are nearer to the axis, the angles of incidence of the neighbouring rays differ

less from one another, because the small arcs, which are near the axis, such as *n b*, *o f*, vary but little in their inclination in regard to the axis; whence it follows, that the incident rays which answer to these small arcs form with them angles that are nearly equal, while at a certain distance, such as *d*, the inclinations of the small arcs experience very perceptible variations, because as the curve rises rapidly in this part, the angles of incidence must themselves vary considerably. Hence also the rays reflected by the arcs near the axis will form between them angles that will vary very slowly, and of consequence there will be always a certain number of those rays that will intersect one another in a very small space situated towards *g*, on the axis of the curve. This space, which we consider as a point, is what is called the *focus* of the rays that flow from R. We here see a new application of the principle, that quantities which approach their limit vary by very slight differences (675), so that there is always a certain space where we may suppose them nearly constant, and where their actions in a manner condense. The limit in the present case is the incidence which takes place on the side of the arc *h n*, and of consequence all these rays will intersect in points less distant from the circumference *b n m*.

798. Let us suppose the radiant point to be at an infinite distance from *n*: in this case, the focus *g* will be exactly in the middle of the ray *c n*. This is what is called the *focus of parallel rays*, because at an infinite distance the incident rays that bordered on the axis become apparently parallel.

On the contrary, in proportion as the radiant point shall approach the centre, the caustics will recede from the circumference *b n m;* and when the radiant point shall arrive at the centre, all the incident rays being then reflected on themselves, the caustics will be reduced to a single point that will be confounded with the centre *c*.

If the radiant point descend afterwards below the centre, the caustics will rise above it, in such manner that they will form angles with the axis continually smaller, at the places where they mutually intersect; and when the radiant point has arrived at the middle of the radius *c n*, the reflected rays nearest the axis becoming parallel (636), the caustics will separate from one another and extend to infinity at their superior parts.

The radiant point continuing to descend, the reflected rays will be found in two different circumstances; for, on the one hand, the angles of incidence of the rays *r o*, *r i*, &c. (fig. 123) being constituted upon arcs slightly inclined to the axis, the analogous reflected rays *o δ*, *i s*, instead of intersecting, will diverge from one another *; whence it follows, that if we prolong them below the arc *b n m*, they will be their prolongations, that will intersect by forming a new caustic at *p*, *z*, &c. On the other hand, the angles of incidence of the rays in the directions $r k$, $r x$, &c. taking place on arcs that rise rapidly, the corresponding reflected rays will be thrown towards one another, and will intersect so as to form the caustic $\mu \omega \varphi$, more or less distant from that which answers to it on the other side of the axis, whereas the caustics produced below the arc $b n m$, will have a point of intersection at *p* (*g*).

---

* The incident rays are very nearly in the same case, with respect to the arc *n i*, as if they fell on a plane mirror.

799. The caustic $\mu \omega \varphi$ will descend towards the arc $b n m$ in proportion as the point *r* shall itself approach that arc; for then the angles of incidence of the rays $r k$, $r x$, &c. always becoming smaller, the reflected rays $k \vartheta$. $x \zeta$, will themselves form with the arc $k m$, angles that will go on diminishing, and they will consequently incline more and more towards the base, and their intersections be nearer the arc $b n m$. What we have said here of this arc equally applies to every other that forms a part of the concave surface of the mirror. Let us now examine the consequences that result from these various propositions relatively to vision aided by convex mirrors.

800. Let us suppose, first, that the object be the radiant point R (fig. 122), situated above the centre. In all the positions in which the eye can see the image, it will refer it to some point of one of the caustics $a g$ and $g s$: for example, if it be situated in such manner that the reflected rays, $h t$, $f t$, (fig. 124),

---

(*g*) It was not consistent with the nature of our author's plan, to enter into the doctrine of caustic curves: but as some of the readers of this work may wish to know the best methods of ascertaining these curves, whether resulting from reflection or refraction at different surfaces, they may be referred for ample information to various of the earlier treatises on fluxions, particularly to *Hayes's Fluxions*, *Hodgson's Fluxions*, and *Stone's* translation of *L'Hospital de Analyse des Infinements Petites*.—Tr.

after having crossed at *t*, have the small degree of convergence that is suitable to the position of the eye at *o*, the eye will see the image at *t*, that is, between the mirror and the centre *c*.

If the point R (fig. 122) be placed in this centre, then the image will be confounded with the object and as it were absorbed by it, so that wherever the eye be situated it will not be able to perceive the image. For a similar reason, if the eye itself occupy the centre, the image from one point, wherever situated, will be invisible to that organ, and it will be able to perceive only its own image, which will be very confused and will cover the whole surface of the mirror.

In every position of the point R, between the centre and the focus of the parallel rays, the image will always appear before the mirror; but it will be above the centre, since the caustics then are themselves higher than that centre.

The image will be very confused when the point R shall be exactly in the focus of the parallel rays, because these rays will mingle with those which, more remote from the axis, will converge towards the eye, and will thus have respective positions the reverse of those which are requisite to distinct vision.

801. Lastly, let us conceive the point *r* (fig. 123) to descend below the focus of the parallel rays: then, according to the different positions of the eye, the image will appear either before or behind the mirror, or rather the eye will see it at the same time on both sides of the surface of the mirror; for if this organ can receive only the reflected rays, such as $o\delta$, is, which diverge from one another, on issuing from the mirror, the image will only be seen behind, at the point *z*, where these rays prolonged meet; and because the rays $o\delta$, is, diverge less than the incident

rays ro, ri, from which they proceed, it is clear that op will be greater than or, and iz than ri; from which it follows, that the image will appear at a greater distance behind the mirror than the real distance of the object before it.

If, on the contrary, the eye be able to receive only the convergent rays, such as $l\omega$, $k\omega$, prolonged beyond the point where they met at ω, so that the diameter of the pupil occupies the distance $\vartheta\lambda$, the image will appear in that same point ω.

Finally, if the eye be placed towards the point ε, in such manner that the pupil may admit at the same time the rays which belong to the two caustics $\mu\omega\phi$ and pz, it will see one image of the luminous point before the mirror and another behind it; and as each caustic has its corresponding one on the other side of the axis, it may happen that the spectator will, with both eyes, see the image quadrupled.

802. Instead of a simple radiant point, let us suppose an object of some extent, and consider the rays only that proceed from its extremities. All we have said of the point r will apply to each of these extremities, as well as to every intermediate point.

When the image is seen behind the mirror it will appear amplified and always direct; for then the concave mirror does not differ from the plane mirror, except in this, that it renders the two sides of the visual angle subtended by the magnitude of the image more convergent towards the eye, which does not at all alter the position of the image, but increases merely its extent. In the same case, the image will appear more remote from the mirror behind, than the object will be before it, for we may then reason with respect to every point of the object, as we have done (800) with regard to a single radiant point. In fine, we may conceive that the image must undergo an alteration of form, since its different points cannot have the same respective positions as the corresponding points of the object, as is the case when we use a plane mirror.

803. There is a singular circumstance attending the phenomena we have been considering, which is, that in proportion as the object approaches the mirror, the apparent distance of the image behind the mirror is increased, and the size of the image increased at the same time; so that the same thing happens to this image, as to an object whose dimensions should augment while it removed farther from us: and thus, while in ordinary vision we always judge an object to be of the same size when it removes to a distance from us, because by estimating the additional distance we rectify the mistake which the diminution of the image at the bottom of the eye would otherwise occasion in the opinion we form of its real magnitude; here, on the contrary, where the distance and magnitude of the image increase at the same time, the adjudged magnitude must also increase in a considerable degree, since, on the supposition even that the apparent distance remained the same, an augmentation of the dimensions of the image would suffice to make us conclude it to be greater in fact.

804. When the object is above the focus of parallel rays, in which case the image is seen before the mirror, that image is always reversed. To understand the reason of this we have only to recollect, that at the same time that the radiant point R (fig. 122) descends towards the mirror, as far as the focus of the parallel rays, the caustics, on the contrary, recede from the mirror. Now we may consider two radiant points situated one above the other as the anterior and posterior extremities of one and the same object. Then the caustic which will produce the image of the

anterior extremity, or of that which is nearest the mirror, will be at a greater distance from this mirror than the caustic appertaining to the posterior extremity; from which it follows, that the whole image will be itself situated in a contrary sense to the object.

But to comprehend still more distinctly the cause of this inversion, let us suppose that, R being a radiant point, there is an eye situated at *o*, in such manner that R *z* is the axis of the pencil of incident rays, and *z o* the axis of the pencil of reflected rays, by means of which the eye sees the image *r* of the point R on the caustic *a g*. Let us conceive that the axis R *n* moves to the right, by turning on the centre *c*, to take the position R′ *n′*; the caustic will follow this motion without changing its situation relatively to the axis, and the eye will see the image of the point R′ on some part, *r′*, of the caustic *a′ g′*; that is to say, at the place where it will be touched by the axis, *z′ o*, of the pencil of reflected rays, proceeding from the incidence according to R′ *z′*; whence we may easily judge, that the image of the radiant point has moved in a contrary way to the point itself. Hence if we suppose R, R′, to be the two extremities of an arrow, the position of the image, *r r′*, of that arrow will be reversed; and we may conceive at the same time, that this is owing to the circumstance of the axes R *z*, R′ *z′*, of the pencils of incident rays having crossed one another at a point, *x*, before they met the mirror, which does not take place when the image is seen without being reversed.

In the same case the image is smaller than the object, because the incident rays *x z*, *x z′*, being divergent towards the mirror, cannot, by passing to the contrary state in consequence of reflection, take a degree of convergence equal to this divergence;

so that the angle $r o r'$, under which the eye sees the image, is smaller than that under which it would see the object at the same distance.

805. Let us now suppose the object placed below the focus of the parallel rays, and the eye in one of the positions in which it sees the image before the mirror: in this case the image will be direct; for we have seen that the motion of the caustics took place then in the same way as that of the radiant point (799), while that point approached the mirror. It hence results, that both the anterior and posterior parts of the image will have the same position, in regard to the mirror, as the corresponding parts of the object, and accordingly the whole image will be turned to the same side as the object.

In this same case, the image will be larger than the object; because the axes of the pencils of incident rays that flow from the extremities of the object, not intersecting before their arrival at the mirror, are thereby rendered much more susceptible of converging after reflection; and the magnitude of the angle under which the image is seen is from the same circumstance considerably enlarged.

This image appears at the side of the mirror, as we may judge from the position of the caustic $\mu \omega \varphi$ (fig. 123), and others that concur in the formation of the image. On the contrary, we can always place ours in such manner as to perceive, in the space answering to the middle of the mirror, the images of objects situated above the focus of the parallel rays; and they are these images that produce the most surprising illusions of all. We can so dispose the mirror and the object, which shall be a nosegay, for example, that both being screened by some other body, a person entering the room shall perceive only the second nosegay produced by reflected light, and shall be greatly astonished at its disappearance, when, by approaching towards it, he removes from the situation in which it was visible to him.

806. Concave mirrors are employed in the construction of several kinds of telescopes, of which we shall in the sequel give some account. Those metallic ones are preferred, which present but a single image of the object; and they are commonly formed of ingredients the choice and proportion of which are such, that the surface of the metallic mixture is white, and thereby disposed to reflect the more light. But these mirrors are apt to tarnish, and are much inferior to those made of platina, from the double advantage which this metal has, of resisting all the causes of alteration, and possessing a density that greatly increases its power of reflection.

That metallic mirrors may answer the end of the observer, their form, which is part of a sphere, must be executed with the nicest precision, and their polish be very complete, or they will render the images confused by absorbing a considerable portion of the rays. The difficulty of effecting these two objects led Newton to imagine that mirrors made of glass, and quicksilvered, would, when carefully done, merit the preference *; but the event did not answer the expectation of this great geometrician; and at present scarcely any but metallic mirrors are used for telescopes and other instruments in which the effects of reflection are combined with those of refraction.

807. When the rays of the sun, which come to us in directions very nearly parallel, fall on the surface of a concave mirror, in such a manner that the ray which flows from the centre of that luminary is confounded with the axis of the mirror, reflection makes

---

* Opticc Lucis, lib. 1, pars. 1, propos. 7.

them coincide nearly in the focus of the parallel rays; and their concentrated force will excite in the bodies that are exposed to it there a heat sufficiently strong to set them on fire, or melt, or vitrify them, according to their nature: from which circumstance this kind of mirror has received the name of the *burning mirror*.

808. A body on fire, situated in presence of a concave mirror, also sends to the surface of that mirror rays which, after reflection, unite in a common focus; but, besides that they have in themselves much less energy than the solar rays, it results from their sensible divergence, that those which fall near the axis are much less condensed in a given space, which takes from the focus a considerable portion of its activity. We may cause their incidence to take place in parallel directions, by employing two mirrors, the diameter of which shall be about 40 centimetres (15 inches), and the curvature such, that the distance between the focus and the reflecting surface shall be as nearly as possible 40 centimetres. We raise these mirrors vertically in such manner that their concavities turn towards each other, and then withdraw them to a distance from one another of 10 metres (30 feet) or more. We then place at the focus of one a burning coal, the heat of which is kept up by blowing it regularly towards the side nearest the mirror. The rays which fall on the mirror becoming parallel after their reflection, will meet in these very same directions the surface of the other mirror, where a second reflection will make them concur in the focus of the parallel rays; and they will thus become sufficiently active to kindle tinder or a piece of amadou, or set fire to gun powder which may be presented to that focus.

809. Father Kircher was the first who thought of substituting for a concave mirror several plane mirrors; so disposed, that the sun's rays reflected at their

surfaces might converge towards the same point. He employed five only of these mirrors, which he so arranged that the concurrence of the rays should take place at a distance of more than 32·5 metres (100 feet), and he found the heat there to be scarcely supportable. "Now," adds this philosopher, "if five mirrors produce so considerable an effect, what would a hundred or a thousand do, arranged in the same manner? They would excite so violent a heat, that it would set fire to every thing, and reduce all to ashes *."

Several philosophers have since undertaken experiments directed to that end; but the kind of polygonal mirror, erected in the Botanic Garden at Paris, in 1747, from a suggestion of the celebrated Buffon, exceeds every thing that had been attempted prior to that period, both as to effect and ingenuity of contrivance †. This mirror was composed of 168 plates of tinned or silvered glass, capable of moving in every direction and of being fixed at different degrees of inclination, so that there could be given to the whole a form more or less concave and the focus be thrown to different distances. This mirror set fire to wood at ficiently extensive for their foci to reach to the distance where the Roman fleet must have been at anchor. But the fact is not impossible, if we suppose him to have employed the combined action of a multitude of plane mirrors; and we have proofs more than sufficient to convince us, that this great geometrician was capable of forming the idea.

Convex Mirrors.

811. The effects of the convex mirror are much less various than those of the concave mirror, and consist simply in representing the image to us behind the mirror, smaller than the object and nearer the reflecting surface. This is the inverse of what takes place when the image is seen behind the concave mirror; but in the same case, the two mirrors represent the image alike in a direct position.

Let *b n m* (fig. 126) be a part of the circumference of one of the great circles of the convex mirror, and R a radiant point placed in the plane of that circle. If we suppose that the reflected rays which appertain to the incident rays R *n*, R *o*, R *f*, &c. be prolonged behind the surface of the mirror, till each shall be cut by the following one, the intersections *g*, *r*, *p*, &c. of those rays will produce a caustic, *g s*, situated on the same side of the axis, and there will be formed a second, perfectly similar, on the opposite side, so that the two caustics will intersect in a point, *g*, situated on the axis.

In proportion as the radiant point shall remove from or approach the arc *b n m*, the caustics themselves will remove from or approach it by contrary motions; and if the radiant point be supposed at an infinite distance, the point, *g*, where the caustics intersect will be in the middle of the radius *c n*; from which it follows, that it is in the same place where the focus of the parallel rays is situated.

812. If the eye of the observer be in the plane of the arc *b n m*, the eye will see the image of the radiant point in some one or other of the caustics: for example, if the situation of the eye be such, that the rays R *f*, R *h*, after being reflected in the direction of the lines *f x*, *h u*, arrive at the eye, the image will be seen at the point, *p*, where those same lines prolonged behind the mirror meet.

813. The image will always appear nearer to the mirror than the object is; because, from the property which the convex mirror has of occasioning in general a tendency in the rays to diverge (638), it is evident that the reflected rays will diverge more from one another than the incident rays, which will bring the imaginary point of concourse near the surface of the mirror. We may derive the same inference from this also, that the point *g* where the caustics intersect, and which gives the image of the radiant point, when the eye is placed on the axis *c* R, does not go beyond the middle of the ray *n c*, while the radiant point removes even to an infinite distance from the mirror.

814. If we substitute for a simple point an object of a certain extent, its image will be seen in like manner behind the mirror, at a distance less than that of the object before it: at the same time it will appear direct; for, supposing the axis *c* R, fixed by one of its extremities, should move, for example, from left to right, carrying with it the radiant point R; it is evident that the motion of the caustic *g s* will take place in the same way: then if we suppose an object whose two extremities answer, one to the radiant point R, as is seen in the figure, and the other to the place to which the same point has been transferred

by the motion of the axis, the image of this object will be situated behind the mirror, in a position similar to that which the object itself occupies before it; and thus the mirror will, in this respect, not differ from the plane mirror, which represents objects in their true situation.

815. Lastly, the image compared with the object will appear contracted in all its dimensions; for the effect of reflection on convex surfaces being to diminish the convergence of the rays, it follows, that the sides of the visual angle under which the eye perceives the image, converge less than those of the angle under which it would see the object at the same distance, and thus the opening of the angle and at the same time the apparent magnitude of the object must be diminished.

Here another observation occurs that is in a manner the reverse of the one we have made in speaking of concave mirrors (803). The apparent distance and magnitude having diminished together, the estimated magnitude must be likewise smaller.

816. There are mirrors also that are made of a cylindrical or conical form, the effects of which afford a delicious treat to curiosity. Their base is placed in the middle of a drawing that exhibits only irregular traits, a sort of enigmas to the eye, the clue to which is in the mirror, where we perceive the regular figure of some familiar object. Geometry furnishes rules for combining the traits of the drawing with the curvature of the mirror, so that the effect proposed shall result from it. As this mirror represents objects totally different from what they are, we take advantage of its very infidelity and give it purposely a defective image to rectify.

Effects of refracted Light, in regard to Vision.

817. The progress of dioptrics or the science of refracted rays, which is now to engage our attention, has been much slower than that of catoptrics, which relates to reflected rays. The fundamental law of the latter, which consists in the equality of the angles of incidence and reflection, must, from its simplicity, have occurred more readily to the mind; and there is great reason to presume that Euclid, who has applied it to the effects of mirrors in his *Treatise on Optics*, had merely availed himself of what was long before known and established in the Platonic school, whose doctrines he followed. The law by which refraction of light is governed was not known till about the close of the thirteenth century, when a Florentine, of the name of *Salvino Degl'Armati*, invented reading-glasses; an admirable discovery by means of which the eye, more apt than the other organs to feel the effect of age, found all at once a return of years that were apparently lost for ever. The first sketch of the telescope is attributed to the children of a spectacle-

To derive however from the telescope all the advantages which it seemed to promise, the law of refraction must be known. Kepler sought it in vain; but he found, by observation, a kind of rule that was at least very near it, and which taught him that a convex ocular might be substituted for the concave one, which had hitherto been used. Scheiner and Rhata improved upon this, and the latter succeeded in combining lenticular glasses, which had several other ad-

Nassau, by means of which distant objects appeared as if they were near, than he returned from Venice where he heard the report, to Padua where he was mathematical professor, and instantly applied himself to investigate, by the aid of his theory of refractions, what must be the nature of the construction; and the night following he discovered it. He furnished the extremities of a tube with two glasses, one convex, the other concave, and directing the tube towards different objects he found they were enlarged three times in diameter: only six days after he took some of the principal senators of Venice to an eminence, from whence he shewed them several distant objects, as though brought nearer, to their great astonishment. Galileo's first success encouraged him: he soon after made another telescope, which augmented about eight times; and afterwards, sparing neither time nor expense, he constructed one which magnified objects about thirty times in diameter. By means of this instrument it was that he discovered the satellites of Jupiter, the spots of the sun, &c. Having advanced the instrument to this state, he presented one to the Doge, Leonardo Donati, and others at the same time to all the senate of Venice, accompanied by a written paper, in which he explained the structure and wonderful uses that might be made of the telescope both on land and at sea. In return for so noble an entertainment, the republic, almost immediately, more than tripled his salary as professor. These particulars are collected jointly from the second volume of Montucla's excellent *History of Mathematics*, and from the *Life of Galileo* prefixed to the 4to edition of his works, printed at Venice in 1744. We record them here, not only with a view to do justice to Galileo, but to the discernment and munificence of the government by which he was patronised; and know not which most to admire, the zealous and successful application of the philosopher, together with so prompt a publication of the result of his enquiries; or the penetration and liberality of the senators, who, at a time when all mental exertions were either repressed by the frowns of bigotry, or fettered by the prevalence of the Aristotelian dogmas, had judgment enough to appreciate the value of their professor, and spirit enough to reward it.—Tr.

vantages besides that of representing the objects right, which with a single eye-glass were seen reversed.

At last Snellius, a Dutch geometrician, determined the fundamental law of dioptrics, which, according to his ideas of the subject, consists in this, that the cosecants of the angles of incidence and refraction are in constant proportion to each other. Descartes substituted for this proportion the sines of which it is the inverse, and which gives the same law in a more simple form. Furnished with this result, he exerted his scientific powers to investigate what curves were best adapted to concentrate in a single point the rays become divergent by refraction: but the difficulty of making glasses of a form answering exactly to those curves, made him resume the spherical figure; so that from his labours in dioptrics, science was a greater gainer than art. Barrow, for whom the glory was reserved of being master to Newton, if Newton had ever stood in need of a master, has published a valuable work on the same subject, in which he elucidates many points that had been before but imperfectly treated *. The practical part, too much neglected till then, made considerable progress in the hands of Huyghens, to whom we are indebted for a great share of the perfection to which the art of shaping glasses is brought.

Newton, who had so happily explained the law of refraction, by the attraction of the refringent medium, has also investigated the principles of dioptrics in a separate work †, and contrived a kind of telescope that bears his name, in which the effects of convex glasses are combined with those of the concave mirror. But he proposed this merely because he thought

---

* Lectiones Opticæ et Geometricæ, Londini, 1674.

† Opusc. viii, Lectiones Opticæ.

it impossible to remove a striking defect of the ordinary telescopes and glasses, which is that of decompounding light as the prism does, and producing those fringes of false colours with which the objects appear to be bordered, when seen through such instruments. Newton was led to this inference by another, which he was too eager to derive from an experiment we shall presently speak of, that was simple and easy, but the true result of which escaped his attention. For nearly half a century no one thought of repeating this experiment, so difficult was it to perceive an error enveloped in a crowd of important truths. At length, an experiment made by Dollond, a celebrated English optician, in circumstances calculated to render it decisive, and which furnished a result the reverse of Newton's, gave rise to achromatic glasses, the history of which we shall detail when it comes naturally in turn in the order of the subjects we have to discuss; and this discovery opened a new career to the genius of the most illustrious mathematicians, as well as to the talents of the most skilful artists.

We shall examine in succession the effects of refraction in media terminated by plane faces, and in those the faces of which are curvilinear; and, having considered the effects of simple glasses, we shall explain those of instruments in which are combined either curved glasses and mirrors, or glasses only without mirrors.

Simple Refraction in Media terminated by Plane Faces.

818. Let *a* (fig. 127, pl. XX), be a radiant point taken in any medium terminated by the surface *ef*, and which sends towards that surface rays whose di-

rections are varied to infinity. Let us suppose *a n* to represent one of those rays, and *n t* to be the refracted ray, which will approach the perpendicular *n x*, if the medium situated above *e f* be denser than that which is below, or in the contrary case will recede from the perpendicular (fig. 128).

From the point *a* let us draw *a b* perpendicular to *e f*, and take between *a* and *b*, or on the opposite side (fig. 127), a point, *z*, so situated that *z b* shall be to *a b* as the sine of incidence is to the sine of refraction, respectively to the medium above *e f*. It is proved by geometry that if we prolong any refracted ray, as *t n*, till it meet the axis, *a b*, of the radiation, the point, *k*, where it will cut that axis, will be always either on this side of (fig. 128), or beyond (fig. 127) the point *z*, so that this last point will be the limit of all the refracted rays flowing from the point *a* *.

Let us conceive that the incident ray *a n*, while its extremity *a* remains fixed, approaches the axis *b k* by its other extremity *n*. The angle of incidence, *b a n*, being diminished, the angle of refraction, *x n t*, will be diminished also; and the point *k* will have approached the point *z*. We hence conclude that when surface *ef*, are at a small distance from the axis, the refracted rays form at a place very near the point *z*, a kind of imaginary focus; for, from the principle that every quantity when approaching its limit varies by degrees that are extremely small (675), the rays which have their concourse near the point *z*, must be denser than in any other part, or abound more in a given space *.

819. Let us suppose that the different rays *an*, *ai*, &c. (fig. 129), flowing from the point *a*, fall at the same time on the surface *ef*, at perceptible distances from the point *b*, and on the same side of the axis. Their prolongations below *ef* will successively cut that axis in points which will be farther from the point *z*; from which it follows, that they will intersect in different points, *d*, *c*, *m*, &c. situated to the left of the axis (fig. 129), or to the right (fig. 130).

If we consider the rays *an*, *ai*, as the extreme rays of all those which, in flowing from the point *a*, fall on the small space *in*, situated in the plane *abf*, their imaginary point of concurrence will be at the point *d*, determinable by calculation. But there are other rays which flow from the point *a*, that fall on other planes, and which disperse from the effect of refraction, in such manner that all those which belong to a small cone whose base should have a diameter equal to *in*, have their points of concurrence disseminated in a small space near the point *d*, so that there will then be no focus, properly speaking †. The determination of the point that is, as it were, the centre of action of all these rays, so that they may be supposed to flow from this point as from a radiant point, is a delicate problem which has occupied the close attention of different philosophers, and has been resolved by them in different ways. Newton places this point nearly at the middle of the distance between the point of concourse of the extreme rays and the point *p* of the axis *.

---

* Barrow, Lect. Opticæ & Geomet. p. 42, No. 12, 13, 14, &c.

† s'Gravesande, vol. II, p. 766, No. 2701.

What we have said furnishes an explanation of the different phenomena ascribed to refraction in media separated by plane surfaces. We shall confine ourselves to the cases where light passes from a rarer to a denser medium.

820. If we place a small object in water, and the eye be situated above the object, it will see the image at a distance from the surface of the water that will be only three-fourths of the real distance; for the first distance is to the second, from what has been said (118), as the sine of incidence is to the sine of refraction, that is to say, as 3 is to 4, when the light passes out of water into air.

In general, the refraction of rays which pass from a rare medium into a denser one, of which the surface situated on the side of the eye is a plane surface, makes the image be seen nearer to that surface. For if we suppose a radiant point situated at *a* (fig. 130), and that *t l* represents the diameter of the pupil, the imaginary point of concurrence of the refracted rays *t n*, *l i*, will always be within the triangle *b a n*, whence it follows, that it will always be nearer the eye than the point *a*.

821. Place some object at the bottom of an empty basin, and let several persons stationed round it withdraw to a distance till the edge of the basin conceal the object from them: pour water into the basin, and

---

* Opuscul. xviii, Lectiones Opticæ, Scholium ad propos. 8.

the object will instantly be visible to each of them, on the supposition that his eye has remained in its fixed position.

It follows also, that a basin filled with water does not appear so deep as when it was empty, because all the points of the surface of the bottom approach towards the eye.

822. If the object have a certain length, such as ab (fig. 131), and be situated parallel to the surface of the refringent medium, its length will appear increased; for then the visual angle aob, by means of which the eye perceived the object with the simple sight, will be augmented so as to correspond with the angle $mo'n$, under which the organ sees the image of the object ab (i).

823. A stick that is partly immersed in water, in an oblique direction to the surface of that liquid, appears broken at the place of its immersion, so that the image of the part under water rises above that same part. For let ef (fig. 132, pl. XXI) be the surface of the water, ha the stick, and o the position of the eye. Among the rays which the point a, considered as a radiant point, sends towards the surface ef, there will be one, such as an, which after its refraction at

(i) Some readers may be apt to conclude from the above, that while the object ab, when posited parallel to the upper surface of the water, appears augmented in length, it will still seem rectilinear; but the fact is that, in such case, the apparent shape is curvilinear. Indeed the curve under which the object would then appear, bears a considerable analogy to the superior conchoid of Nicomedes, holding the same relation to an ellipse as that curve does to a circle; the surface of the water would be an asymptote to the image of the object, and correspond to the directrix of the conchoid. Curves of this kind have been treated, by Dr. Barrow, in the 16th of his *Lectiones Opticæ*; by M. Mairan, who calls them *Curves de Reflectoire*, and traces their analogy to caustics by refraction, in *Mém. Acad. Sci.* 1740; and by Bouguer and others under the title of *Anaclastic Curves*. See also *Leybourn's Mathematical Repository*, vol. II. pa. 364. old series.—Tr.

the point *n*, will direct itself towards the eye, and cause it to see the image of the point *a* as if posited in *x*; whence it follows, that the part under water, *g a*, will have for its image the line *g x*, and the stick will appear broken at the point *g*.

Let us conceive the stick while fixed at one of its extremities, *a*, to rise by the other till it coincides with the line *a b*, perpendicular to *e f*, and let us suppose that the eye be still situated at *o*; the apparent magnitude of the part under water will be equal to *x b*, much shorter than the real magnitude *a b*. In general, an object plunged vertically into water always appears contracted, and the more so as its upper extremity approaches nearer the surface of the water; so that the *minimum* takes place, for a constant position of the eye, when the upper extremity of the object is on a level with the liquid.

Every thing remaining in the same situation, if we take the object out of the water, and it be of a slender form, we shall, with a sort of surprise, see it become longer and larger, by a rapid developement, as it were, of all its parts.

In proportion as the object comes out of the water, we perceive, by the aid of reflection, the image of its exterior part, and that image is at first shorter than that of the interior part, seen by refraction; but as this last diminishes, while the other augments, there is a term where they are of the same length. Now the image seen by reflection is equal, during every instant, to the part of the object situated out of the water, this liquid performing here the office of a plane mirror (785). Let us suppose that at the moment when the two images have the same length, we measure the part out of the water, and then, instantly withdrawing the object from the liquid, measure the part that was plunged in the water; we shall always find, by the proportion between the two, the quantity which the part under water appeared, from the effect of refraction, to be less than it really was: for example, if the part out of the water be half that of the immersed part, we may conclude that the apparent length of this last part was also half its real length.

Double Refraction.

We owe the knowledge of the phenomenon of double refraction (641) to Erasmus Bartholinus, who having looked at the image of a line through a transparent rhomboid of carbonate of lime (calcareous spar), observed that the image appeared double. This rhomboid came from Iceland, where many are found that are perfectly limpid. Bartholinus was extremely surprised at what he saw, and his imagination heightening the wonder, he affirmed, that this phenomenon, buried in the country where bodies destined to produce it abounded, proved to naturalists a truth of which they were before ignorant, that the cold of northern countries, instead of weakening the rays of light, gave them, on the contrary, additional energy *. The truth is, that all climates furnish transparent carbonate of lime susceptible of doubling the images of objects, and that many other substances, which we shall hereafter cite, partake of the same property.

The explanation of this singular effect has exercised the sagacity of many distinguished philosophers, at the head of whom are Huyghens and Newton; and nothing can shew more forcibly the difficulty of the subject than the variety of opinions that was adopted

* Erasmi Bartholini Experimen. Cristalli Islandici disdiaclastici; Hasniæ, 1770; dedic. ad Regem Frider. III.

by those philosophers, each attempting, without being stopped by what had been done by others, to open to himself a distinct career; so that in the midst of this conflict of authorities and results upon a subject that has been turned about in so many different ways, it appears equally difficult to select from what has been advanced already, or to advance any thing new. We shall begin with describing the principal circumstances of the phenomenon; we shall afterwards give an account of the most remarkable of those theories which have been devised for explaining it, and shall add the results to which our own enquiries have led us, and which have served as data both to appreciate the value of those theories, and to sketch an outline of what we conceive should afford a complete solution of this so delicate a problem.

325. Let us conceive *e b* (fig. 133) to represent a rhomboid of carbonate of lime, in which *a* and *n* are the two larger solid angles * or those which are composed of three plain obtuse angles equal to one another †; and let us draw the shorter diagonals *a e*, *b n*, of the two faces *h a d e*, *g b c n*, which we shall consider as the bases of the rhomboid, by supposing them to be

into two parts, of which one, *t l*, will be on the prolongation of the incident ray, as in the ordinary case, and the other, *t f*, will recede from the preceding one, by advancing towards the small solid angle *b*, that is, there will take place a double refraction of the ray of light.

827. We shall now call the ray *t l*, the *ordinary ray*, the ray *t f*, the *ray of aberration*, and the distance, *f l*, of one from the other, taken on the lower base of the rhomboid, the *amplitude of aberration*.

828. If the incident ray *s t* fall obliquely on the surface of the rhomboid, it will divide itself always into two parts, of which one, which will be the ordinary ray, will be refracted by approaching the perpendicular at the point of immersion, by a law analogous to that of common refractions, and which is such that the sine of refraction is to the sine of incidence constantly as 3 to 5; the other part, which will be the ray of aberration, will recede always from the preceding, to approach the angle *b*, whatever be the direction of the incident ray. We shall presently see what is the law of this second refraction.

829. If the incident ray be in the plane of the principal section *a e n b*, the ordinary ray and the ray of aberration will also be both in the same plane; a result respecting which all the theories agree.

830. Let us now suppose that a ray of light passes through two rhomboids situated one above the other. If the principal sections coincide in the same plane, or are respectively parallel, whether their lateral edges *a b*, *e n*, incline the same way, or a contrary way, as in (fig. 135), none either of the ordinary rays or of the rays of aberration that shall come out of the first rhomboid will be decompounded in passing into the second, but will be refracted there according to the same law as in the first rhomboid.

831. If the two rhomboids be so disposed that their principal sections cross at right angles, then each of the rays that issue from the first rhomboid will still remain simple on entering the second; but the functions of those rays will be changed, that is to say, the ray which was the ordinary one in the first rhomboid, will direct itself in the second like the ray of aberration, and reciprocally.

But in all the intermediate positions, that is, in those where the principal sections shall be inclined to one another, each of the two rays that issued from the first rhomboid will divide itself anew in the second, into an ordinary ray and a ray of aberration, and will be directed conformably to the incidence of the ray of which the two are the subdivisions. These interesting results are Newton's *.

It should be observed, that the rays of aberration have this in common with the ordinary rays, that in passing from the rhomboid into the air through a face parallel to that at which they entered it, they take a direction parallel to that of the incident ray.

From these same results it is easy to explain the phenomena observed when we look at an object through a rhomboid or through two rhomboids placed one upon the other.

832. Let us consider the first of these cases, and suppose, for greater simplicity, that *a e n b* (fig. 136), being the principal section of the rhomboid, there is a visible point, *b*, placed at a certain distance below the rhomboid, and an eye situated at *s*, above the upper base. Among the rays which the point *p* sends towards the rhomboid, there is one, such as *p l*, of which the part *l t*, considered as an ordinary ray, after repassing into the air, arrives at the eye in a

---

* Optice Lucis, lib. iii, quæst. 25.

direction, *t s*, parallel to *p l*. The other part, which is the ray of aberration, takes a direction such as *l z*, by throwing itself towards the acute angle *e;* and as, after its emergence at *z* according to a line *z x*, this ray becomes again parallel to *p l*, it is lost to the eye. Now, among all the other rays that flow from the point *p*, there will be a second, of which the direction, *p o*, will approach so near that of *p l*, that *o r* being the ordinary ray that proceeds from it, the ray of aberration, *o u*, crosses the ray *l t* at the point *k*, and after its emergence at *u*, follows a direction, *u s*, parallel to *p o*, and that terminates in the eye. We conceive that this supposition is always possible, since we can take the ray *p o* under whatever inclination we please with respect to *p l*. The eye will then see two images of the point *p:* one in the direction *s t*, which will be the ordinary image; the other in the direction *s u*, and that will be the image of aberration. As to the ray *o r*, it is evident, that, because of its parallelism to *p o*, after its emergence at *r*, following a line such as *r m*, it cannot pass to the eye.

In proportion as the point *p* shall approach the line *b n*, the point *k* will descend towards that same line; and when the point *p* shall touch *b n*, the point *k* will be confounded with it, in such manner that the double image will still exist.

833. It is remarkable that one of the two images, *videlicet*, that which is seen in the direction *s u*, and is produced by the ray of aberration, always appears more remote than the other from the upper base of the rhomboid. This difference in the distance may be rendered very perceptible by describing a circle on a sheet of paper, and observing, through the rhomboid, the two images of that circle which will cross each other, at the same time that one will be seen in a lower position than the other.

834. In the experiment represented by figure 136, the image of aberration, seen in the direction *s u*, appears nearer to the obtuse angle *n*, than the ordinary image, the place of which is in the direction *s t*; which is the inverse effect of that which the ordinary rays and rays of aberration proceeding from one and the same incident ray present. This inversion is a consequence of the intersection of the rays *o n* and *l t* at the point *k*.

This same course of the rays by intersected directions serves to explain an interesting experiment for which we are indebted to the celebrated Monge. Take hold of the rhomboid with the forefinger on the ridge *a b* (fig. 133), and the thumb on the ridge *e n*, and place its upper base, *a d e h*, as near as possible to the eye, so that one of the two images of the point *p* may be situated, with respect to yourself, behind the other. Then slide gently under the rhomboid a piece of paper which, while thus applied to the lower base, shall move from *b* towards *n*, till it conceals one of the two images. You will remark with surprise, that this image of which the paper first conceals the sight, is not that which is on the side where the paper is, one of their bases, put them on a piece of paper marked with a spot of ink. If the homologous faces of the two rhomboids are parallel, the eye will see but two images of one and the same point, as if there were merely a single rhomboid; only they will be more remote from each other. Things remaining in the same state, gently turn the upper rhomboid round upon the lower one, and you will presently see two new images, which will at first be faint in their appearance, but will afterwards gradually increase in intensity, while the first two images will become more and more feeble, and will at last disappear before the rhomboid that is in motion shall have completed a quarter of its revolution: beyond this term, still continuing to turn it, the same effects will take place in the inverse order; that is, the first two images will appear again, and their tint, faint at first, will be gradually reinforced, while the other two will diminish in intensity, till, towards the completion of half a revolution of the moveable rhomboid, they will become extinct[*]. The principal sections being then turned in contrary directions, but on one and the same plane, as figure 135 represents, the eye will no longer see more than two images; but they will be much nearer than in the first case, and if the two rhomboids were exactly of the same height, only one image would be seen. Complete the revolution of the upper rhomboid, and the preceding effects will appear again, observing a retrograde course.

We have thus far considered the results merely of such observations as obviously present themselves to any eye not deficient in attention. Let us now examine the different opinions of philosophers, each of which has its partisans, respecting the precise determination of the law by which the phenomenon is governed, and the physical effect upon which it depends.

---

[*] These different facts are all subject to exceptions when the visual ray is extremely oblique and takes certain positions; for we then see but two images where we ought to see four, and *vice versa.*

836. Huyghens, who made the propagation of light consist in general of a kind of undulations of a circular or spherical form, referred the law of ordinary refraction to the same source; and to account for the double refraction that took place in carbonate of lime, he supposed that light, in penetrating a rhomboid of that substance, produced in it undulations of two forms, one spherical, as in other bodies, the other spheroidal, confined entirely to the same present case; and it was to the last of these undulations that he attributed the refraction of the ray of aberration *. He manages this hypothesis with so great subtlety, that the estimates he derives from it, relatively to the angles of incidence and refraction of the ray of aberration, appear to us in general to approach the truth. He even obtained a very remarkable result, which we shall presently state, that is equally adapted to a theory founded on the emission of light in a direct line (*k*).

fringent media exerted on the moleculæ of this fluid, attributed likewise the refraction of aberration to an attractive force, which however was peculiar to the same substance of carbonate of lime, and had its centre of action situated towards the small solid angle of the rhomboid; and the following is the determination to which this illustrious geometrician was led, relatively to the law of the phenomenon.

837. Let us suppose *s t* (fig. 134) to be still an incident ray perpendicular to the base of the rhomboid, and situated in the plane of the principal section *a e n b*. The ordinary refracted ray being *t l*, situated on the prolongation of *s t*, the ray of aberration, which will necessarily throw itself towards the small solid angle *b*, will be situated like *t f*, which makes with *t l* an angle of 6° 40′. Now the amplitude of aberration, *f l*, which would result from this incidence, equally took place, according to Newton, with respect to all the inclinations of the ray *s t*, whether it remained in the plane of the principal section or departed from it; whence it should follow, that the amplitude of aberration is constant, not only as to its length, but also as to its direction, which is always parallel to the shorter diagonal, *b n*, of the base of the rhomboid *.

838. Other philosophers have conceived that they could bring the refraction of the ray of aberration under the ordinary laws; and the principles on which their hypothesis is founded are these: Among all the incident rays which can meet the upper base of the rhomboid obliquely, there is one, such as *s′ t′*, so situated, that the ray of aberration, *t′ f′*, which proceeds from it, is on its prolongation, that is to say, the refraction of aberration then becomes evanescent, so

---

* Optice Lucis, lib. iii, quæst. 25.

reconcile with this hypothesis the results of observations made with two rhomboids, in which the rays sometimes merely change their functions, and sometimes are subdivided anew, in passing from one rhomboid into the other *.

We are much more disposed to range ourselves here again on the side of Newton, when we consider the extreme simplicity of the law admitted by this celebrated geometrician for the refraction of the ray of aberration. This law besides is allied to another physical cause we shall presently state, and which gives a very happy explanation of the phenomenon that arrested Huyghens in his progress. But there is an important correction to make in this law, from the observations we are about to state; which have, however, this advantage attending them, that any person may easily repeat them.

842. If we place a rhomboid of carbonate of lime on a paper marked with two points, and cause the distances of those points to vary, in regard to a fixed position of the eye, we shall find there is a term, where, instead of four images, we shall see but three; in this case, two of the first images unite together and form one of a deeper tint.

If at the same time the eye be in the plane *a b n e* (fig. 133); that the same effect may take place, it will be necessary for the two points to be on the diagonal *b n*.

If the eye afterwards remove from the position where it saw two images confounded, these images will separate, and the more so the more the eye shall change its position; and to see them coincide anew, the distance between the two points must be increased, if the visual ray, in varying its inclination, approaches the point *e*, and diminished, if the visual ray shall be inclined in a contrary sense towards the point *a*. We suppose this ray never to be out of the plane *a b n e*, in which case, for the four points to be reduced to three, it is necessary to leave the two points always in the direction of the diagonal *b n*.

---

* Quo artem pacto id fiat, nihil reperire potui, quod mihi satisfaceret. Tractatus de Lumine, p. 69.

843. If the visual ray be out of the plane *a b n e*, the effect will be different. The following is what we observed in that case. Let *b n* (fig. 137) be the same diagonal as in figure 133, and *p* and *r* the two visible points. Let us conceive that, the visual ray being first inclined towards *e*, and situated in the plane *a b n e* (fig. 133), the eye makes a circular motion from *e* towards *h*; the observer will not be able to see two of the images coincide, except by placing the points *p*, *r*, (fig. 138), in a direction inclined to the diagonal. Let us suppose the point *p* to be fixed; the point *r* must be placed to the right of the diagonal, as in *r'*; while the visual ray shall approach nearer and nearer to a plane that shall cut the principal section at right angles, the necessary distance between the point *r'* and the diagonal *b n*, will increase, and will be the greatest possible, when the visual ray shall be in the plane we have mentioned. Beyond that plane, proceeding from *h* towards *a* (fig. 133), the distance must be diminished, by always leaving the point *r'* (fig. 137) on an oblique line that diverges on the side of *n*, relatively to the diagonal. When the visual ray shall fall anew, but in a contrary way, on the plane *a b n e* (fig. 133), the distance will vanish. If the ray continue its revolution from *a* towards *d*, the same effects will take place in a contrary order; that is, to obtain the coincidence of the images, the point *r'* must be situated on the other side of the diagonal, as in *r''* (fig. 137).

844. Now let *s t* (fig. 138) be a ray of light that falls, in any direction, on the upper base of the rhomboid. Let *t r* be the ordinary ray, and *t p* the ray of aberration, in which case *p r* will be the amplitude of aberration; and let *p p′*, *r r′*, be the emergent rays, which, from what has been said, will be parallel to *s t*. Instead of the ray *s t*, let us suppose two visible points, one at *r′*, and the other at *p′*, that transmit rays from the rhomboid in every imaginable direction. It is evident that among those rays, that which shall follow the direction *r′ r*, will be so divided at the point of emergence, that *r′ t* will be still the ordinary refracted ray; for, on account of the parallelism of the rays *s t*, *r′ r*, considered successively as incident rays, the refracted ray, *r t*, will perform the same function respecting each of them. For a similar reason, the ray that shall flow in the direction *p′ p* will be so decomposed in the rhomboid, that the ray of aberration will still be *p t*.

The proposition will be always true, whatever may be the positions of the visible points along the lines *r′ r*, *p′ p;* from which it follows, that if we suppose one to be in *r*, and the other in *p*, *p t o* and *r t s* will be the paths of the rays that will arrive at *s*, and every thing will take place as in the hypothesis of the incident ray *s t*. Things remaining thus, let us suppose an eye placed at *s;* that eye will see two of the four images given by the two points, being confounded in the direction *s t*. Hence, every time this union takes place, the distance, *p r*, between the two points is the amplitude of aberration, relatively to an incident ray that should have the direction in which the eye perceives the single image formed by that union.

Now, we have seen that it was necessary in that case to alter the distance between the two points, in proportion as the position of the visual ray itself varies: whence it follows, that the amplitude of aberration is not, as Newton had supposed, a constant quantity.

845. Nor is it more constantly parallel to the shorter diagonal *b n;* for we have seen that when the visual ray was not in the plane *a b n e* (fig. 133) (and the same may be said of every other plane parallel to that), the two images cannot be made to concur so as to form a single image, but by placing the two visible points on a line inclined to the diagonal. Therefore, in all cases of this kind, the amplitude of aberration, which measures the distance between the two points, itself makes an angle with the diagonal.

It would seem that Newton, having made experiments with rhomboids of an inconsiderable height, and being unable to measure with sufficient precision the distances and positions of the rays of light which he introduced immediately through those bodies, must have been hurried away by the simplicity of the law that seemed to present itself to his observation.

We have endeavoured to ascertain the true principle by which the refraction of the ray of aberration is governed, but in cases only where that ray is situated in the plane *a b n e;* other avocations not permitting us to extend our enquiries farther. We shall now give the result we have obtained, represented by the help of a construction which will be readily understood.

846. We have seen (838) that when the incident ray *s t* (fig. 133) was perpendicular to *a d e h,* in which case the ordinary ray continued its course in the rhomboid, the ray of aberration threw itself towards the small solid angle *b.* Let us suppose that the line *a x* (fig. 139, pl. XXII), let fall from the angle *a* perpendicularly on the diagonal *b n,* repre-

sents the ordinary ray. In that case, if we take xy equal to a third of bx, and draw the line ay, this last line will represent the ray of aberration relative to the perpendicular incidence upon ae.

Now let st be an incident ray falling obliquely on ae, and tl the ordinary refracted ray, the position of which it is easy to determine, from the proportion of 5 to 3 between the sines. The position of the ray of aberration, tf, is demanded.

From the foot of the line ax, draw xo, to form, with ax, an angle of 60°; then from the foot of the ordinary ray, tl, draw lm parallel to xo. On lm take the part lu, equal to xz. The line tf, drawn from the summit of the ordinary ray and through the point u, will be the direction of the ray of aberration relative to the incidence according to st.

If we suppose the incidence to take place in a contrary way, according to $s't'$, then the ordinary ray being represented by $t'l'$, the ray of aberration, $t'f'$, will be between the preceding one and the angle b, and we shall have the amplitude of aberration by a construction similar to that which we have indicated relatively to the incident ray st.

847. We thus see that lu, or $l'u'$, is a constant quantity, while the amplitude lf, or $l'f'$, is necessarily a variable one. If we suppose the two incidences, st, $s't'$, to be equal in contrary directions, we shall have $f'l'$ smaller than fl, in such manner that their sum will be double the amplitude xy, relative to the perpendicular incidence. This amount is then itself a constant quantity. Huyghens had deduced this same result from the properties of the ellipsis, whose figure he attributed to the waves of light, which, in his opinion, was the cause of ordinary refractions. But in the theory we propose, this result is found to be ascribable to the properties of right lines, and it is

even proved that it always takes place, whatever may be the value of the angles bxo, xag, provided we take lu, or $l'u'$, equal to xz. Among all the possible cases, we have chosen that which appeared to us the best adapted for observation; and it is remarkable, that this is the precise case where the line ox forms with ax an angle of 60°, while it forms with ao an angle that is nearly $101^\circ\frac{1}{2}$, that is, equal to the larger angle of the primitive rhombus [*].

848. The observations upon which the same theory is founded, have appeared to us to furnish a very satisfactory explanation of a remarkable fact we have already mentioned, which is, that the image produced by the ray of aberration is always more sunk than the other below the upper base of the rhomboid.

To understand the reason of this difference, let us remark first, that the rays by means of which we see the image of a point situated behind a diaphanous medium, form a cone, the base of which is contiguous to the surface of the medium nearest the eye. Above that surface, they bend themselves back towards the eye, from the effect of refraction, by forming a truncated cone, the smaller base of which confounds itself with the base of the first cone, and the other base, which is more dilated, has a diameter equal to that of the pupil by which the rays enter the eye.

---

[*] Let us conceive $t'l'$ to be applied upon tl, by reversing the base $f'l'$ of the triangle $l't'f'$, in such manner that the point f' falls upon the point e, on the other side of the ray tl, and the point u upon the point p. If we draw lp and up, the last will evidently be parallel to bn, because of the equality of the angles ulf, plc, and that of the lines lu, lp. Also, the line fc will be equal to the sum of the two distances, $lf+l'f'$. Now, if we suppose the ray tl to change its inclination, by remaining fixed at its extremity l, the lines tc, tf, on the hypothesis of lu, lp, being constant, will remain fixed themselves by their points p, u, while their upper and lower extremities will move along the lines ae, bn. Therefore, in all cases, we shall have $tp : tc :: up : fc$. But it is easy to perceive that, because of the parallels ae, up, bn, the relation $\frac{tv}{tc}$ will be constant, therefore the relation $\frac{up}{fc}$ will also be constant; and since up is constant, fc will be so likewise. Now the nearer the ray tl approaches to parallelism with the perpendicular tm, the nearer fl approaches to an equality with xy. Hence, if we suppose the direction of tl to differ infinitely little from the perpendicular, we may make the line fc, or the sum of the two lines fl, $f'l'$, equal to $2xy$. Therefore, since this sum is constant, it will be the double of xy in all cases. We perceive that this demonstration is independent of the position of the line ox, or of the angle it makes with the diagonal bn,

Whatever opinion we adopt respecting the precise distance at which we perceive an object seen by refraction (819), it is certain, all other circumstances being equal, that that distance is greater when the two diameters of the bases of the truncated cone differ less from one another, the effect of which is, that the summit of the same cone, prolonged in imagination behind the refringent surface, is more remote from that surface.

This being granted, let us conceive *a n* (fig. 140) still to represent the same rhomboid, and that, *p* being a visible point situated on the inferior base, *p o k s r* is the broken cone, by means of which the eye perceives the ordinary image of the point *p*. We suppose first, this eye to be so placed, that the visual ray is in the plane of the principal section. All the rays of aberration corresponding with the ordinary rays, of which the cone *p o k s r* is the assemblage, are lost to the eye, in consequence of what has been said above. But there is a second cone * formed by the other rays of aberration, by means of which the eye sees the image of aberration of the point *p*, and here all the corresponding ordinary rays are in like manner lost to the eye.

Let us take, in the cone *k p o*, the two rays *p k*, *p o*, which terminate at the extremity of the diameter situated perpendicularly to the diagonal *a e;* and let us restore for an instant the two rays of aberration that correspond to them: it is obvious that those two rays must be at the extremities, *n*, *l*, of two oblique lines with respect to the diagonal *a e*, since in this case the amplitudes of aberration diverge in regard to that diagonal, as we have observed before (843). Therefore, if the eye were placed so as to receive those very rays that are lost to it, their distance being greater than the distance *k o*, the point where those rays are imagined to meet behind the surface *a d e h*, would be farther off than that of the ordinary rays, *k r*, *o s*.

---

* We avoid representing this second cone, that the figure may not be too complicated.

We then conclude that the laws by which the rays of aberration are refracted, tend, in general, to render the distance between those rays, taken on the two opposite sides, greater than that between the ordinary rays, taken according to the same condition.

Now as this augmentation of distance, which we find on comparing together the ordinary rays that compose the cone *p k o s r*, and the corresponding rays of aberration, allowance being made for circumstances, ought always to take place with respect to the other rays of aberration that are within the scope of the eye and enable it to see the image of aberration, it follows, that the refraction of aberration tends to enlarge the smaller base of the truncated cone more than the ordinary refraction does. Hence, if we suppose this cone prolonged behind the refringent surface, the point of its axis, where all the directions will appear to converge, ought to be more distant with regard to the eye and the refringent surface, than the corresponding point of the cone formed by the ordinary rays. Consequently, the apparent place of the image of aberration will be also more distant than that of the ordinary image.

If we conceive the visual ray to be inclined in a contrary manner towards the point *a*, we shall, by applying the same mode of reasoning, obtain similar conclusions.

If the visual ray comes out of the principal section and throws itself sideways, so as to approach the point *h*, for example, then $k' o'$ (fig. 141), being the lower base of the truncated cone, the lines $k' n'$, $o' l'$, will incline the same way. But the line $o' l'$ will deviate more than the line $k' n'$, from the direction parallel to $a e$; whence it follows, that we shall still have $n' l'$ greater than $k' o'$, though in a less degree than when the visual ray coincided with the principal section. Therefore, the image of aberration will also be seen in this case farther off than the ordinary image; but the difference of distances will be less perceptible than in the first case; which has appeared to us conformable to observation.

849. We shall add some details here on the subject of double refraction, with regard to the different natural substances which partake of that property. Of those substances, carbonate of lime and of sulphur are hitherto the only ones that exhibit two images of the same object seen through two of their parallel faces; which appears to us to arise from the circumstance of their primitive forms being oblique-angular parallelopipeds, whereas the other forms arise from a solid in which the bases are at right angles with the lateral faces. To perceive the double image, by means of the latter, the two faces through which we look at the object must be inclined towards each other; but it may happen even then that the double refraction shall become evanescent and the two images com-

bined, which will always be the case when either of the two faces of the refringent angle is perpendicular or parallel to the axis of the primitive form, which depends upon the nature of the substance. Thus in emerald it is the first position that occasions the union of the two images, and in sulphate of barytes (heavy spar) it is the second.

With respect to carbonate of lime, which gives in general the double image of an object seen through two parallel faces, we may, by preserving the parallelism, so order things, that the image shall appear single. All that is necessary is to form a rhomboid of that substance, so as to generate two triangular faces, that may intercept the two solid obtuse angles, *a*, *n*, (fig. 133, pl. XXI), and be perpendicular to the axis that passes through these angles. The image of a point seen through these two faces will be single, provided the visual ray be perpendicular to them, and the point be situated on its direction; for if the eye deviate on either side, the two images that coincided will separate.

To understand the cause of this, it must be remarked, that in the case where the image appears single, in consequence of the conditions we have indicated, the ray of light emanating from the visible point could not be subdivided in the interior of the rhomboid, unless its part of aberration should throw itself in preference towards one in particular of the acute angles *e*, *c*, *g*. But the position of that part of aberration being the same relatively to these three angles, it thence obtains a sort of equilibrium, so as to continue a joint course with the perpendicular ray belonging to the ordinary refraction, and thus the eye sees the two images confounded; but as soon as, the eye beginning to depart from the perpendicular, the incident ray, that caused it to see the image of aberration, is forced, in passing through the rhomboid, to take an inclined position tending more towards one of the angles *e*, *c*, *g*, than towards the other two, that moment the two images separate.

850. Nothing now remains but to give a distinct view of the physical cause on which the phenomenon depends. Though that which Newton supposed may appear singular at first, the more it is studied and the closer it is examined and compared with observed facts, the more reasonable it appears.

This great philosopher supposed the moleculæ of light to have two kinds of poles, upon which the matter of carbonate of lime exerted a particular action, whose centre was placed in the region of the small solid angle. Conformably to this idea, he considered each individual ray as an infinitely thin quadrangular prism, in which all the poles of the nature just mentioned, were ranged on two opposite faces, which are called *faces of aberration*. When the ray, in penetrating the rhomboid, for example, in going from the upper base, *a d e h*, to the lower one, *b c n g*, presented one of these faces to the solid angle *b*, the force in question attracted it to it, whereas when it presented to the same angle one of the other two faces, which may be called *faces of ordinary refraction*, the matter of the rhomboid exerted no other action on it than was common with ordinary media.

This being laid down, among all the individual rays of which a beam of light that falls on the surface of the rhomboid is formed, some will have their faces of ordinary refraction, and others their faces of aberration, turned towards the small solid angle. The beam will then be divided into two parts, one of which will undergo ordinary refraction only, while the other, attracted by the force residing in the small solid angle, will be subjected to the refraction of aberration.

This hypothesis acquires additional probability when we apply it to the phenomenon of the four images produced by two rhomboids placed one upon the other (835), and to the variations which the images exhibit as to their intensity, in proportion as the upper rhomboid is made to revolve round the lower one. These effects shew that the pencil of aberration, in which all the faces of aberration were turned at first, were turned exactly towards the region from whence the force that acts on them emanates, is gradually subdivided, in proportion as that region, during the rotation of the rhomboid, changes its position, so that some moleculæ after others escape the attractive force, to undergo the ordinary refraction. The contrary happens with regard to the rays of the other pencil, which at first had their faces of aberration at right angles with the region from which the force that produces the aberration emanated; for these faces becoming by degrees more favourably situated with regard to the force in question, are some after others subjected to its action, till the whole is at last in the case of aberration. An affinity is supposed to be observable here, whose intensity increases or diminishes, accordingly as the corpuscles on which it acts are more or less exposed to its action, in such manner that the number of corpuscles attracted itself augments or diminishes by proportional quantities.

Vision by means of a single Glass terminated by curvilinear Surfaces.

We shall begin with the kind of glass that is of a more general utility, and bears the name of *lenticular glass,* or simply *lens,* on account of its form, which represents two spherical segments, applied to one another by their plane faces.

851. We have already seen (646), that among the rays which fall on the surface of a lenticular glass in directions parallel to the axis, those which are near that axis, after experiencing two refractions, one on passing into the glass, the other on repassing into the air, meet nearly in a common point which is called the *focus* of the parallel rays.

Let us conceive now that there is a radiant point, *r* (fig. 142, pl. XXII), situated in the place of that very focus. Among the rays which this point transmits towards the lens in all imaginable directions, those which recede a little from the axis, such as *rg, ri,* will come out from the opposite side, parallel to the same axis, according to the directions *mp, uz.* But the rays more remote from *rx,* such as *rb, rf,* being more divergent than the rays *rg, ri,* and thereby less disposed to be inflected by the quantity requisite to become parallel to the axis on repassing into the air, will come out according to the directions *es, ln,* which will diverge respectively, or with regard to the axis, in such manner however that the divergence will be less than that of the incident rays.

It thence follows, that if we prolong the emergent rays *zu, se, yq,* their prolongations will intersect at the points *v, a, c,* &c. farther from the lens than the point *r,* so that their intersections will form a caustic, as in the case of reflection at the surface of concave or convex mirrors. To curves of this kind the name of *caustics by refraction* is given.

852. If we suppose the radiant point to be situated between the focus of parallel rays and the lens, then the rays which will fall on the small space *g i*, being more divergent than when they issued from this same focus, it follows, that on their return into the air they will continue to diverge, instead of being parallel, and at the same time the divergence of all the others will increase.

853. Instead of a simple radiant point, let us conceive an object, A B (fig. 143), of a certain extent, and placed in like manner on this side the focus of the parallel rays, and let O be the position of the eye. By again confining ourselves here to the course of the rays that flow from the extremities, A, B, of the object, we may still suppose two cones of light, *c* A *e*, *f* B *h*, so situated, that after being first bent back on entering the lens, and then returning into the air, they proceed to pass through the pupil of the eye, O. In this case the rays, such as A *c*, A *e*, which sensibly diverge in coming from the point A, will, after their emergence in the directions *k y*, *p u*, have no more than the small degree of divergence that accords with the conformation of the eye; so that all the cones sent from the different points of the objects will go to paint the image of it on the retina.

If we prolong on the side opposite to the eye the rays *y k*, *u p*, and all the others which it is necessary to represent as comprised between them, we may apply to all these rays what we have said of the rays *y g*, *s c*, *z u* (fig. 142); namely, that the intersections of their prolongations will not coincide in a common point. But as those which compose the cone that came from the point A (fig. 143) are very near together, the concurring points of the prolongations we are speaking of will be comprised within a very small space, in so much that here, as in the other analogous cases mentioned before (819), the directions of the different rays are imagined to concur in a single point, that, as it were, is their centre of action.

854. In all circumstances similar to the one we are considering, we see the object direct and at the same time amplified; for the eye perceives it under the angle *l* O *z*, manifestly more open than the angle A O B, under which it would be seen by the simple sight.

855. In the same circumstances also, the object appears to have a greater degree of clearness. For let *r* (fig. 144) be one of the points of the object, which we will suppose to be the middle point, and *h i* the diameter of the pupil; all the rays comprised in the angle *p r s* will pass through the aperture of the pupil, in the directions *q h*, *l i*, and the intermediate lines. Now if we prolong *r p* and *r s* towards the eye, and suppress the lens, the rays comprised in the angle *p r s* will spread over all the space *g k*, which is larger than the diameter of the pupil; from which it follows, that the pupil will receive more rays through the intervention of the lens, than in the case of simple vision; and though there are some rays that are intercepted in their passage through the lens, the loss being more than compensated by the effect of refraction, an increase of light will always be the result.

856. Lastly, the point of concourse of the rays that bring to the eye the image of every point of the object, is more distant than in ordinary vision; for the refracted ray *s l*, for example, in repassing into the air will depart from the perpendicular at the point *l*, according to a direction *l i*, so that its prolongation, *l z*, will pass to the right of the point *s*; whence it

follows, that the rays *i l*, *h q*, will meet in a point, *z*, more remote from the eye than the corresponding point, *r*, of the object.

857. With regard to the judgment we form of the dimensions and distance of the image, every body knows that it appears in reality larger than the object, and that we are led at the same time to suppose it nearer, though the rays which delineate it at the bottom of the eye are directed as if they proceeded from some fictious object, more remote from the eye than the true one. But this is only a sort of precipitate judgment into which we are drawn at first by the increased magnitude, and to which the increased clearness likewise contributes. Take a long needle, and pass it slowly under a lens, in a transversal direction, and at a proper distance from the glass; compare attentively the position of the image with that of the object, and you will observe that the image is in appearance more remote, especially if the lens be tolerably large. By augmenting the distance, and passing the needle to and fro in directions parallel to itself, you will discern the difference still better; for there are moments in which we must be on our guard against the illusion that tends to make us judge what appears larger to be nearer to us.

858. Let us return to the consideration of a simple radiant point, *r* (fig. 142), and suppose this point, in coming from the focus of parallel rays, to recede gradually from the lens. In that case, the rays that will fall on the small space *g i*, being less divergent than in the case where the focus of parallel rays was their point of departure, will be thereby determined even to converge in relation to one another, or with the axis, behind the lens: at the same time the divergence of the rays, *e s*, *q y*, more remote from the axis will diminish, and there will be a term at which all the

emergent rays will be thrown towards the axis, as we see in figure 145 (pl. XXIII). In this same case, of the rays situated on the same side of the axis, each will be intersected by the following ray, and we may conceive a caustic that passes through all the points of intersection.

859. Let us again substitute for a simple point an object, A B (fig. 146), of a certain length, supposing it still placed beyond the focus of the parallel rays; and let us, for the greater simplicity, consider only what takes place with respect to the middle point, R, and the two extreme points, A, B. The point R is again here the common summit of an infinitude of cones which fall on different parts of the surface of the lens. Now, among all these cones, that of which the axis R *t* is perpendicular to the refringent surface *m t n*, is composed of rays that manifestly meet in a common point, *r*, behind the lens, and thus form there a focus.

In like manner there flows from each extremity an infinitude of cones more or less oblique, the bases of which correspond to different parts of the surface *m t n*. Now, among all these cones, there is one whose rays meet nearly in a like point behind the lens; and it is that of which the axis A *c* is so situated that, after being refracted according to the line *c h*, it meets the surface *m x n* in the place where the tangent at the point of incidence *h*, on the concave arc, is parallel to the tangent at the point of incidence *c*, on the convex arc. In this case, the refracted ray *c h* passes through the middle of the lens. We may conceive there will always be a cone sent from the point A, that will satisfy those conditions; for, if we suppose that the line *x t*, which forms part of the axis of the cone sent from the point R, while remaining fixed by its middle, which coincides with the centre of the lens, turns round that centre in such manner that its extremity *t* describes the arc *t m*, and its prolongation is refracted continually in the space between *t m* and R A, that prolongation will successively abut upon different points situated between R and A, and will end at last by coinciding with A. Now it is evident that at this term the line *x t* will have the position *h c;* from which it follows, that if A *c* be now considered as the incident ray, the refracted ray will be *c h*.

We see also that the ray A *c*, in repassing into the air after its refraction at *h*, will take a direction, *h a*, parallel to that which it had at first; and if we suppose the lens to have but little thickness, we may consider the ray *h a* as being apparently on the direction of the ray A *c*, and as forming the same line with it.

It thence follows, that the cone to which the axis A *c* belongs is that, among all those coming from the point A, which approaches nearest to the circumstances of the middle cone, whose axis is the line R *t:* now this will be also the cone of which the rays will apparently meet behind the lens in a common point, *a*.

The same reasoning may be applied to all the cones proceeding from other points of the object A B, by which we perceive that the rays of all these different cones will have their foci nearly on a line, *b r a*, parallel to the line A R B. Now, wherever there is a focus, an image is formed of the radiant point to which that focus belongs; and hence it is that if we place a sheet of paper at a proper distance behind the lens, we shall see the image painted on the paper. In the same case we see the reason of the image being reversed, since the only cones whose rays are collected together, if we may so express ourselves, in a manner to produce foci, intersect in the middle of the lens. On this principle is founded the construction of the dark room *(camera obscura)*, of which we shall speak hereafter.

860. It is easy to conceive that the lens, in the experiment we have been citing, is nearly with respect to the paper that presents the image of the object, what the crystalline humour is with respect to the membrane that covers the bottom of the eye, and receives in like manner the images of objects. Only the lens acts by itself in producing the image we see on the paper, while the different humours of the eye unite with the crystalline in the representation of objects on the retina.

861. Things remaining the same, instead of supposing in the situation of the image *a b*, a piece of paper on which the eye perceives that image, as in a picture, by means of the rays that are reflected from its different points, let us take away the paper and conceive the eye itself to be situated behind the lens, to observe immediately the image of the object A B*. It is in the first place evident, that the organ will no longer be able to see it by means of the rays *f b*, *h a*, &c. which had served to render it present to the eye when it was painted on the paper, since the axes of the cones to which those rays belong continue to diverge, whereas it would be necessary they should converge towards the eye.

Also the mere view of the kind of change of scene which has taken place in this case, is sufficient to shew that the rays themselves have altered their course; for we then commonly see two images of the object: besides, each image is seen by one eye only, and in such manner that the image which is situated on the left is painted in the right eye, and *vice versa;*

---

* The eye in this case ought to be situated beyond the focus of the parallel rays that is on its side.

which we may ascertain by shutting and opening each eye in turn. Lastly, though the rays which, in this case, arrive from every point of the image to one or other of the organs of vision, continue to intersect between the lens and that organ, as we shall presently see, we then no longer refer this image to its true place, that is, to the situations where the rays intersect, but it appears to us behind the lens, nearly as when the object is situated on this side of the focus of the parallel rays, unless, as in the present case, it is reversed and smaller than the object. We shall speak soon of a particular instance in which the two images are reduced to one, and which we then see with both eyes.

862. Our object now is to prove that among the different cones which, from the different points of an object, A B (fig. 147), are directed towards the lens, there will be always some that will be bent by refraction so as to produce the effects we shall describe. Let us suppose the two eyes to be stationed at *o* and *o′*. From the point B, there comes a pencil of light, *e* B *u*, of which the extreme rays, B *e*, B *u*, are refracted in the lens according to the lines *e s* and *u z*; and as the emergent ray which issues at *s* is farther from the axis than that which issues at *z*, it will incline towards the latter; so that the two rays, after intersecting at *b*, will proceed towards the eye, and enable it to perceive at that same point, or near it, the image of the point B. By similar reasoning we may prove that the pencil A *d* tends to produce a like effect on the eye *o*, with respect to the image that is formed at *a* of the point A; and so of all the other intermediate points of the image *a b*. What we have said of this image applies of itself to the image *a′ b′*, which the eye *o′* perceives by means of the pencils A *g* and B *f*; and there is no difficulty in conceiving

why the two images are both reversed and smaller than the object.

The circumstance we are considering here is analogous to that which takes place when, by means of a concave mirror (801), we perceive the double image either behind or before the mirror; because the eye, which is accustomed to bring together and identify, if we may so speak, the two images in ordinary cases, where they almost exactly coincide, receives them here in situations so much apart, that it no longer falls into the illusion which led the observer to suppose them united into one.

863. But it may happen that the eyes, by varying their motion, may be in a position under which the four pencils intersect two by two in places where the rays themselves have their intersections; in which case the points *a*, *a'*, on the one part, and *b*, *b'*, on the other, will be confounded, as is represented in figure 148, and then there will no longer be more than one image, which will be seen by both eyes at once.

The first phenomenon, *videlicet*, that which produces the two images represented by figure 147, has this singularity attending it, that the places to which we refer the images are not situated between the lens and the object; and it is thus that this singularity is explained. We see each of the images in question but with one eye, as we have stated; from which it follows, that there is but one of the optic axes directed towards each image, and thus one of those conditions is wanting which are commonly necessary for us to judge of the position of objects (758), and are especially so when the vision is effected by means of a glass that draws the eye in a manner out of its ordinary state. We may add, that, in the present case, the position of the real object beyond the glass, leads us to judge the image to be situated on the same side.

864. If we present a tarnished glass on this side of the lens, at the place where the foci of the cones belonging to the different points of the object are formed, we shall perceive the two images on this same glass; as if a ground were necessary to this picture, traced in a manner in the air, to divert the eye from the illusion to which the presence of the lens subjects it: and what proves, that, in this case, they are the prolongations of the very rays received by that picture, which, in penetrating the glass, proceed to copy on the bottom of the eye the traits of the drawing, and not of new rays reflected by the posterior surface of the glass, is, that if there were but a single image, it would appear or disappear accordingly as we shut one or the other eye, as would take place if the tarnished glass were not employed. We have thus already one way of referring the image to its true place.

865. But we shall exhibit an experiment that produces the same effect without any intervening object. Place a lens in a vertical position, at such a distance from a very perceptible object, as a metallic ball on the top of a vertical iron rod, that you may see two images of this ball through the lens; then withdraw your eyes gradually, and the two images will approach each other and become continually smaller. At length there will be a term where they will meet, and the two optic axes being then directed to that single image, you perceive it distinctly on this side of the lens. This is the case which figure 148 represents.

Now if, continuing to look steadily at the image, you draw gradually nearer to the lens, you will still see the image single though you advance beyond the point where it before appeared double, and it will besides come forward of itself, as if to meet you. It has sometimes happened in such circumstances that we have brought the image so near as within seven or eight centimetres of the eye (3¼ inches), which was easily determined by placing a finger by the side of the image; and, to see the image again double, we were obliged to begin the experiment anew, after having looked at other objects, as if to efface the last impression, and call up afresh the illusion of which it had taken the place.

866. Eyes the most perfectly formed by nature are liable from age to different alterations: their humours become dry and contracted; the cornea and crystalline flatten; light is less inflected in them by refraction, and of consequence the summits of the pencils which form themselves in the eye fall no longer on the bottom of the organ, but tend to reach a limit beyond it. The image then, instead of being composed of distinct points, is merely a confused assemblage of small circles that encroach on one another. We hence conceive why those persons whose sight begins to fail from the effect of age, and to whom have been given the name of *presbytæ*, are still able to read distinctly by placing the book farther from their eyes; for then the cones of light transmitted from the different points of the printing or writing having longer axes, while their base remains equal to the circle of the pupil, the consequence is, that the rays diverge less in their passage to the eye than when the book was nearer, and that divergence renders them more apt to converge, by means of their refraction in the humours of the eye, which may bring their point of concurrence sufficiently near to make it correspond on the retina. But when, by reason of the further increase of this defect in the eye, old age is deprived of the resource just adverted to, it is supplied by means of glasses a little convex, called *spectacles*, the

effect of which is to diminish the divergence of the rays that in this case reach the eye as if they came from a greater distance; so that when the glasses have the degree of convexity suited to the state of the eye, the rays meet at the bottom of the organ.

867. When a lens is presented to the solar rays, in such a manner that its axis coincides with their direction, these rays, after being twice refracted, once on passing into the glass, the other on repassing into the air, assemble again in a certain space which is situated on the axis and is called the *focus* of the lens. Bodies exposed to the activity of this focus undergo alterations similar to those produced by the focus of the concave mirror (807), and the lens has then the name of *burning-glass.* Tschirnausen and Hartzoeker have made lenses of this kind that were 13 decimetres, or four feet, in diameter.

The larger the lens the more rays are contained in the focus, which is in reality a collection of an infinitude of foci, whose dispersion over different points of the axis deprives a great portion of the rays of their activity. The effects they produce are rendered much more powerful, by making them pass through a second lens that is smaller and very convex: this lens, besides the advantage resulting from a greater number of rays, possesses that of compressing them in a smaller space, where their action is exerted with far greater energy.

868. The effects of convex glasses being properly understood, those of concave ones, which have in general the contrary properties, will be attended with no difficulty. These last render the objects seen through them smaller than they really are, because the two sides of the visual angle, which measures the apparent magnitude of the object, losing part of their convergence in passing through the glass, that angle becomes smaller than it would be to the simple sight.

869. These glasses also render the objects less clear, because each pencil of light is dilated, from the effect of refraction, and of consequence fewer rays reach the eye than if the pencil had retained the same dilatation as when it departed from the object.

870. Lastly, if we suppose the rays which enter the eye to be prolonged on the opposite side, their point of concourse will be nearer the eye than in the case of ordinary vision. This also is owing to the dilatation of the pencils, which renders the rays more divergent towards the eye, or, which amounts to the same, more convergent in the contrary sense, as if there were no glass.

It is true, that when we see an object through a concave glass, the first impression leads us to suppose it farther off than when we see it with the naked eye, because it appears smaller; but looking more carefully we soon correct this mistake; for if we make an experiment here similar to the one we mentioned (857) when speaking of the lenticular glass, that is, if we draw backward and forward, behind the glass, a thin and long object, and compare the apparent distance of the part seen by refraction with the other part which projects beyond the glass and is seen by the naked eye, we shall clearly perceive that the first distance is less than the other.

871. Those who by a natural defect have the cornea and crystalline humour too convex, are called *myopes*. This figure, which increases the quantity of refraction, tends to render the rays of such pencils as are formed in the eye more convergent, so that the point where these same rays meet is on this side of the retina. Myopes see distinctly those objects only which are near, which send towards the eye rays more divergent, and thereby less disposed to converge, through the effect of refraction in the crystalline and other

humours. This imperfection being the reverse of that which affects the eye of presbytæ, is remedied by the use of a glass slightly concave; which, increasing the divergence of the rays received by the eye, prolongs the pencils that are formed in the organ, and causes their summits to fall more exactly on the retina.

872. Myopes seem to have a fondness for minute objects: in general they write a very fine hand, and read in preference works that are printed in a small type, because by choosing dimensions suited to the narrow scope of their sight, they continue to embrace a greater number of objects at once. They have the habit also of closing in a certain degree the eyelids when they wish to see objects distinctly that are otherwise distant for them. Two advantages have been ascribed to this natural motion. On the one hand, by contracting the lid, access is given to a smaller portion of light. Now those who are myopes see objects that are situated at a distance indistinctly, merely because the cones that are formed in the eye, as we have observed in the preceding paragraph, have their summit on this side the retina; so that the prolongations of the rays of which these cones are the assemblage, give rise to new cones, whose base meeting the bottom of the eye depicts a small circle there, instead of a simple point. Accordingly, when the number of rays introduced into the eye is diminished, that small circle is contracted, and the vision becomes less confused. On the other hand, the eyelids, by closing, exert a pressure on the organ that diminishes its convexity, and in part restores it to the form most favourable to clearness of vision.

873. When we would examine very minute objects, such as the stamina and pistils of flowers, or the different parts of an insect, we commonly make use of a

small lens whose focal distance is very short, or of a glass globule: this is called the *simple microscope.* Suppose first, that we employ a lens, *m n* (fig. 149), it is very evident, that if this lens be small, and the eye be at *o*, close to its surface, the angle *a o b*, under which the eye sees the object *a b*, supposed to be very small, will be nearly the same as in the case of the naked sight: for the rays *a o*, *b o*, will pass very near to the middle, *c*, of the lens, and will of consequence come out apparently parallel to the directions they had when they came from the object; so that their respective inclinations will scarcely be deranged by the lens. It thence follows, that the single microscope represents objects nearly of the same apparent magnitude as when seen immediately by the eye at the same degree of proximity. Let us consider then what advantage is gained by using a lens.

874. A small object placed very near to the naked eye, produces only a confused image, because the rays that compose the cones of light, transmitted from the different points of the object, being very divergent, cannot be sufficiently refracted in the humours, for the summits of the interior cones to terminate on the retina. The points where the rays meet tend to a greater distance, and in this respect all men may be said to be presbytæ. Of this we shall easily be convinced by looking at a small object that is very near to the eye; its image will appear considerably amplified, because the eye being, if we may so speak, on this side the limits which bound the field of its ordinary observations, judges of the real by the apparent magnitude, in the same manner as when it is beyond those limits, that is to say, when the object is very distant from it; but the image at the same time will have a kind of misty appearance, for the reason we have assigned.

If, under the same circumstances, we look at the object through a small hole made with a pin in a piece of paper, the image will appear much clearer; because the hole will permit only a small portion of the rays belonging to each cone to pass through it, and thus the small circles which the interior cones will form on the bottom of the eye being reduced nearly to simple points, their impressions will be much more distinct.

875. Now observe what the simple microscope does: it sensibly diminishes the divergence of the rays which compose the cones emanating from the object, and makes them reach the eye under the same degree of inclination as if they came from an object situated at an ordinary distance. Of consequence the vision of such object will become distinct, and the image at the same time acquire additional clearness; because the refraction, in this case, collects and condenses the rays, in such a manner that more arrive at the pupil than it would receive without the intervention of the glass (855): moreover, the visual angle remaining the same, the object will be seen under the same apparent magnitude. Thus we know, in general, that a person with good sight sees an object distinctly at the distance of about 22 centimetres or 8 inches; but if the object is very small, the angle under which it is seen at that distance contracts the image so much at the bottom of the eye, that the vision has not sufficient clearness. The microscope assimilates the image to that of an object of very sensible magnitude that should be placed at the ordinary distance we have mentioned, of 22 centimetres, where the direct vision is distinct. It gives the eye the advantage of the augmentation of magnitude, and removes the inconvenience that arises from the too great proximity of the object.

The lens is so disposed that the object apparently coincides with its focus, because in that case the rays of each exterior pencil arrive at the eye in parallel directions or nearly so, which is requisite to clearness of vision, supposing the eye to be well formed.

876. In the same hypothesis, the apparent diameter of the object, seen through a lens, is to the diameter which would have place at the distance at which the eye perceives ordinary objects distinctly, as the angle under which the same eye sees the object placed in the focus of the lens is to the angle under which it would see it at the distance we have stated. Now the two angles subtend equal chords, either of which measures the real diameter of the object, in such manner that each of them forms with its chord a triangle of which the chord is the base. Therefore these angles are to one another nearly in the inverse ratio of the heights of the triangles to which they belong. Now the height of the shortest triangle is the focal distance of the lens, and the height of the longest the distance requisite to distinct vision; whence it follows, that the diameter of the object appears amplified in the proportion of this last distance to the distance of the lens. For example, if we suppose, as before, the distance requisite to the distinct vision of objects of a sensible magnitude to be 22 centimetres, and the focal distance of the lens to be 2·5 millimetres, the diameter of the object will appear increased in the proportion of 88 to 1.

877. We may substitute for a lens a glass globule, which is easily made by melting a small piece of that substance in the flame of an alcoholed wick, to prevent the mixture of fuliginous matter, which would injure the transparency of the glass. Simple microscopes also may readily be formed, by making a small hole through a thin plate of metal, and conveying to the hole a drop of water suspended to the point of a pin,

so that the drop may assume a perfectly round form. But these drops have less effect than the glass globules, because their refractive power is less (*l*).

Vision aided by Instruments formed of several Glasses.

Our remaining task is to exhibit the resources which art has been able to derive from the combination of glasses either with one another or with mirrors, to form those instruments which have been productive of so many discoveries in the hands of astronomers,

---

(*l*) The fluid microscope here described was first suggested by Mr. Stephen Grey, as may be seen in the *Phil. Trans.* Nos. 221, 223, or vol. IV. pp. 97, 120, of the *New Abridgement.* Another fluid microscope has been recently invented by the Rev. D. Brewster, and is described in the 2d vol. of his edition of *Ferguson's Lectures.* Its exterior appearance is much like that of the new pocket microscope invented by Messrs. Jones of Holborn, and described in vol. II. of Dr. Hutton's Dictionary: There is a vertical bar fixed upon a horizontal pedestal; and from the top of this bar proceeds a horizontal arm, which supports a circular case containing the lenses: below this another horizontal arm slides up and down, capable of adjustment by means of a screw, and carrying the usual sliders to hold the object which it is proposed to examine: and upon the pedestal is fixed the frame of a mirror, which has both an inclined and a horizontal motion, in order to illuminate any object upon the slider. The upper circular case is hollow, and contains four or more plano-convex lenses, which are constituted each of a drop of very pure and viscid turpentine varnish, taken up by the point of a piece of wood, and dropped upon a piece of very thin and well polished glass. The lenses thus formed may be made of any focal length by taking up a greater or a less quantity of the fluid. The lower surface of the glass having been first smoked with a candle, the black pigment immediately below the lenses is then to be removed, so that no light may pass but through the lenses. The piece of glass is then perforated at its centre, and surrounded by a toothed wheel, which, when the wheel is put in the upper circular case, may be turned by a common endless screw, so that the fluid lenses shall be brought severally under an eye-aperture properly disposed, and any object be successively examined with a variety of magnifying powers.—Tr.

naturalists, and that numerous class of observers to whom has been given the appellation of the *lynx-eyed literati; savans aux yeux de lynx.*

878. The effects of telescopes and microscopes depend in general on this circumstance, that the first glass exhibits an image in the space between it and the following one, which image that following one conveys in its turn beyond the next glass, and so through the series, in such a manner that the last image becomes as it were the immediate object of vision; and the whole theory relative to this subject consists in ascertaining what is the best construction for rendering this image as distinct, as large, and as clear, as possible. The eye which receives this image constitutes, in some sort, a part of the telescope or microscope, and they form together a single optical instrument, or, if you please, a singular kind of eye, that combines the whole power both of nature and art to raise vision to its highest perfection.

879. The most simple of all telescopes is that which is called the *astronomical telescope:* it is composed of two convex glasses, of which one, *g h* (fig. 150), that is turned towards the object, is called the *object-glass,* and the other, *k n,* situated towards the eye *o,* the *ocular* or *eye-glass.* This last has more convexity than the other, and its focus, *r,* coincides with that of the object-glass *g h,* so that *c l* is equal to the sum of the focal distances. The eye placed at the point *o,* where the other focus of the eye-glass is situated, receives rays whose impressions on the retina represent the object reversed there and very much amplified.

It is easy to perceive, from the mere inspection of the figure, first, that the object-glass *g h* produces in *a b* an image of the very remote object A B, like that of which we have before explained the formation (859), and that it might be received immediately by

—placing a piece of white paper at the distance rc, from the centre of the object-glass. This image is substituted for the real object, and the pencils kbm, nax, &c. which flow from the different points, and of which the rays are merely prolongations of those that have passed through the object-glass, bend in the eye-glass, in such a manner that, on repassing into the air, they concur towards the eye in the directions zo, po, while the rays of each pencil lose nearly all their convergence, which gives clearness to the image on the bottom of the eye. On the other hand, the angle, zop, under which the eye perceives the fictitious object being much larger than that under which it would see the real object, the apparent magnitude is considerably increased; and we prove by geometry that it is to the magnitude under which the object would appear immediately to the eye, as the focal distance of the object-glass is to that of the eye-glass *.

---

* Let A B (fig. 151, pl. XXIV) be the diameter of a very distant object, as the moon for instance. Let m, r, be the foci of the parallel rays, relatively to the object-glass gh, and r, f, those of the same rays with respect to the eye-glass kn. On account of the immense distance at which the object is situated, we may always suppose, that a ray flowing from one of its extremities, such as A, after having passed through the focus m, proceeds to meet the lens gh; from which it follows, that it will come out of it in the direction hn, parallel to the axis Rr, and that after experiencing a new refraction in the lens kn, it will direct itself towards the focus f. Now, conceive another ray, Ac, that passes through the centre of the lens gh. The refracted ray, ca, forming so extremely small an angle with the axis cl, that is in a manner parallel to it, will come out of the lens nk in such a direction, that the point o, where it will cut the axis, will nearly coincide with the focus, f, of the parallel rays. Now the ray Aca may be considered as the axis of the pencil which forms in a one of the extremities of the image situated in the interval between the two lenses; and since the points o, f, as well as the directions of the two rays that terminate at those points, approach so as to be nearly confounded with each other, if we suppose the eye to be situated at o, the angle nfl will, as to sense, be that in which that eye sees through the telescope the semi-diameter of the enlarged image. But, since the object is extremely distant, the interval between the

It thence follows, that we gain on the side of the dimensions by employing eye-glasses of a shorter focus; but at the same time we lose as to the clearness of the image that is painted on the bottom of the eye, because the rays of the same pencil, after having passed through an eye-glass, the focus of which being nearer requires greater convexity, do not also exactly meet on the retina in a common point.

880. The telescope we have been describing serves only for celestial objects, where the inversion of the image is attended with little inconvenience. For terrestrial objects another kind of instrument has been invented, known by the name of the *Batavian telescope* or *Galileo's telescope* (817, note *h)*, which is formed of a convex object-glass and a concave eye-glass, and represents the objects direct. Let us consider the progress of light in this instrument.

When an object is situated behind a convex glass, beyond the focus of the parallel rays, the image which the rays proceeding from the different points of the object form on the other side (861), becomes smaller in proportion as the object is farther off. Now such is the extreme minuteness of that which the object-glass of the Batavian telescope tends to produce, that

---

points o, m, must be considered as nugatory; so that we may suppose the angle AmR, or its equal, cmh, to be that in which the eye would see the semi-diameter of the object with the natural sight. Hence the apparent magnitude will be to the real magnitude as the angle nfl is to the angle cmh. Now these angles being very small and subtended by the equal sides ch and ln, are sensibly to one another as cm, or cr, is to fl.

For if we make cmh, lon, to coincide by their sides ch, ln, as is represented in fig. 152, the angles cmh, coh, which we always suppose to be extremely small, will be nearly as their sines, or as the sides oh, hm, which, in the triangle mho, are opposite to those angles. Now the relation of oh to hm differs in its turn very little from that of co to cm, which are the two focal distances. See Huyghens, *Opera Reliqua;* Amstelod, vol. II, dioptr. p. 134, and Smith's Optics, p. 76.

the space it would occupy on a sheet of paper placed at the proper distance would be sensibly less than the surface on which the objects are painted at the bottom of the eye.

Let *g h* (fig. 153) be the object-glass, and A C, B C, two rays from the extremities of the object, which, after crossing each other at the centre, C, of the object-glass, shall have formed at *a b* a small image of the object. If we place a concave eye-glass, *k n*, between the object-glass and that image, the divergent rays C *s*, C *t*, in passing through this eye-glass, will become still more divergent, and will take the directions *s b′ t a′*; from which it follows, that if the line D *d* represents the diameter of the pupil of the observer, he will see the image of the object of a magnitude, *b′ a′*, much more considerable than that in which he saw it without the intervention of the glass we have mentioned.

Let us suppose C *s*, C *t*, to be the axes of pencils sent from the points A, B; the rays which form these pencils will converge towards the eye-glass, since but for the glass they would proceed to unite in *a* and *b*; and such is the curvature of this glass, that it will render the rays parallel or nearly parallel, so that they will enter the eye in directions proper to produce a clear image at the bottom of that organ.

Lastly, it is evident that the object will appear direct, because the rays that flowed from the points A, B, instead of intersecting, as is generally the case, in passing through the pupil, will intersect in passing through the object-glass, which produces the same effect with regard to the situation of the image.

Such, then, is the effect of the eye-glass, *k n*, that, by its intermediation, the rays which tended to produce the image *a b* in space, paint it at the bottom of the eye in its largest dimensions, as if it were the image of an object situated beyond *z*, and of which the extremities should send rays that, after crossing in this same point, should continue their course without intersecting in the pupil itself, by following the directions *z b′*, *z a′*. The apparent magnitude of the image is to that in which the object would be seen by the naked eye, in the ratio of the focal distance of the object-glass to that of the eye-glass, precisely as in the case of the astronomical telescope *.

881. The space which the telescope permits the eye to embrace is called the *field* of the telescope. In the astronomical telescope the extent of the field depends on the size of the eye-glass, but in Galileo's it is governed by the width of the pupil; because the pencils of light, *s b′*, *t a′*, which isue from the eye-glass, and which include between them all the others that are transmitted from the object, as they go on to separate, pass near the edges of the pupil; while in the astronomical telescope the pencils proceeding from the borders of the eye-glass in converging directions, go on afterwards to intersect in the pupil: further, the telescope of Galileo has less field, which renders it less commodious in use.

882. We remedy the reversed appearance of objects seen with the astronomical telescope, by adding two other glasses so disposed that the foci of the neighbouring glasses always coincide in a common point. These also have the name of eye-glasses, like that which is next to the eye. We may easily judge of the effects of this telescope by a slight inspection of *figure* 154. The rays *e b*, *d a*, &c. which form the image *a b* behind the object-glass *g h*, after having penetrated the second glass, *i l*, cross at the common focus, *c*, of that glass, and of the next, *t s*; they pass

---

* Smith's Optics, p. 79.

through this third glass, beyond which they form a second image, *a′ b′*, which is reversed with respect to the preceding one; and at last the eye-glass *k n* receives them and renders them convergent towards the centre, *o*, of the pupil.

883. The instruments we have been describing, and in general all those known by the name of *dioptric telescopes*, have two striking defects which prevent the images from appearing clear and well terminated.

The first, which is called *aberration of sphericity*, is occasioned by the spherical figure of the glasses, which does not permit the rays very near to the axis to unite perceptibly in a common point (646). Those which are farther off, being more strongly refracted, cut the axis on this side of the same point, so that the focus is in reality a space of a certain extent. The result is, that the principal image, or that which is produced where the greatest number of rays unite, is as it were dimmed by a multitude of other images which render the vision confused.

884. The simplest way that has yet been discovered of remedying this inconvenience is, by diminishing the surface of the object-glass. The extent of this surface is what is called the *aperture* of the telescope, and is measured by the number of degrees contained in the arc that passes through two opposite points of the circular border of the same surface, and through the point where the axis of the object-glass meets it. By narrowing the aperture, the rays which fall at a certain distance from the axis and disturb the vision are intercepted.

885. The defect we have mentioned was at first considered as the only one that rendered telescopes imperfect; but that which arises from the different refrangibility of differently coloured rays has a still more injurious effect on the perspicuity of the images.

To comprehend this thoroughly, let us remark, that the surface of a lenticular glass is nothing else than an assemblage of an infinite number of small planes, of which any two, taken from two opposite sides, are conceived to belong to two faces of a prism, provided they are not in positions where the tangents are parallel. Now, among the rays of one and the same pencil which form a focus behind a lens, there is only the axis that comes out parallel to itself. All the other rays issue at facets inclined with respect to those by which they entered. The result of which is, that a lens causes light to undergo a decomposition analogous to that which takes place by the intermediation of a prism. Let us suppose, for greater simplicity, that a parcel of rays meets a lens in directions that are themselves parallel to the axis of that lens. The rays, after having repassed into the air, will form along the axis a series of foci, of which the nearest to the lens will be that of the violet rays, which are the most refrangible, and the farthest that of the red rays, which have the least refrangibility; the other foci will be situated between these, in the order of their refrangibility. The case is the same with a pencil that makes its incidence in whateverdirection.

886. The effect of the decomposition we have stated exerts its influence on vision by means of magnifying glasses and common telescopes. The differently coloured rays, which form the pencils sent from the different points of the object, being separated from one another on coming out of the object-glass, generate, behind this glass, an image impaired by the diffusion of the foci; and the rays which issue from the eye-glass convey this image to the eye with all its causes of imperfection. The colours produced by the decomposed light are effaced towards the middle of the image, where the rays by their mixture recompose

white; but they become perceptible towards the borders, and occasion there those variegated or rainbow-like fringes which disfigure the images and prevent them from being distinctly terminated. This defect is called *aberration of refrangibility.*

887. Newton, whose discoveries on colours caused this defect to be known, endeavoured to prove how injurious it was to the perfection of catadioptric telescopes, particularly if the instruments were to be shortened to render them more manageable and commodious; and he therefore considered the construction of such a telescope, that should be of a moderate length only, yet give sufficient distinctness to the images, as *a thing to be despaired of*[*].

Under this persuasion, he turned his thoughts to the subject of reflection, and devised a construction in which he substituted for the object-glass a metallic concave mirror. The instrument which he formed from this principle bears the name of the *Newtonian telescope,* and its nature is this:

888. Let AB (fig. 155) be the image of a distant object, produced by means of the concave mirror MVN, in such a manner that SMA, TGA, represent the extreme rays of the pencil transmitted from the point of the object to which the point A of the image answers. If we would make this image pass immediately through an eye-glass, part of it would be intercepted. Now this inconvenience is remedied, by reflecting the image by means of a small plane mirror, *de,* inclined 45 degrees to the axis, HV, of the concave mirror, from which arises a second image, *ab,* that becomes the object of vision. The rays *ar, az,* pass through the eye-glass *kn,* which, as the figure shews, is situated on one side, and, after

---

[*] Newtonii Optice, lib. i, pars 1. propos. 7.

being refracted on repassing into the air, in the directions *u y*, *q h*, nearly parallel, proceed towards the eye placed at *o*, and cause it to see the image amplified under the angle *q o x*. This image is at the same time reversed, in consequence of the properties of the concave mirror we have already explained (804). These instruments have been called in general *catadioptric telescopes*, from their uniting the effects of reflection and refraction combined.

889. In the idea of a telescope thus constructed, Newton had been anticipated by James Gregory, who gave in his *Optica Promota* a description of what he had conceived. He employed two curvilinear mirrors, one parabolical the other elliptical *(m)*; but the difficulty of executing such mirrors, has since occasioned mirrors simply spherical to be substituted in their stead: the largest is placed at the bottom of the telescope, as in that constructed by Newton; the other, which is very small, has its concave side turned towards the first. The image formed by reflection on the large mirror, is received by the small one, which reflects it in its turn. Two eye-glasses are placed behind the large mirror, which has a small

---

(m) Notwithstanding James Gregory is generally supposed to have been the first who conceived the idea of a reflecting telescope, of which he has given the delineation in his *Optica Promota*, published in the year 1695: yet Newton certainly was the first person who demonstrated both its importance and its practicability. And even the honour of having first devised the notion of this admirable instrument must be resigned by Gregory to the Jesuit Eskinard, who distinctly described it so early as 1615, in his *Century of Optical Problems*. It may also be remarked that Gregory proposed the reflecting telescope merely to remedy the spherical errors of lenses; but the object-glasses of telescopes are too small portions of spheres to make the defects, arising from their figure, sensible.

The Cassegrain construction of the telescope differs from the Gregorian only in the form and position of the small speculum, which is convex instead of being concave; and is placed before the principal focus of the great concave, not behind it, as in the Gregorian.—Tr.

circular aperture in its centre, through which the image sent from the small mirror passes. The first eye-glass produces a new image, from which the rays that reach the eye on quitting the second eye-glass proceed in parallel directions.

This telescope represents the objects direct, and is therefore better than Newton's for observing terrestrial objects; but with respect to clearness it is much inferior to it, because the light has an additional glass to pass through; and it is inferior also with regard to the perfection of the image, because the second mirror, which is concave like the first, adds to the little alterations inseparable from the reflection that is made on mirrors of this kind. After all, the construction of catadioptric telescopes requires a multitude of delicate precautions, and many attempts must be made before we can direct them properly towards the objects we wish to observe.

890. Such was the state of dioptrics, when, in 1747, Euler, reflecting on the structure of the eye, conceived an idea that was succeeded by the most beneficial consequences in respect to the progress of this science. It consisted in this, when we look at objects with the unassisted sight, their images are not altered by any mixture of foreign colours. Such inconvenience only happens when the images produced by refraction through a lens, and tinged already with prismatic colours, become the immediate object of vision. Euler hence concluded that the eye had all the properties of an instrument capable of making the aberration of refrangibility disappear; he had no doubt that the different humours of this organ were so arranged as to occasion no diffusion of foci, and he concluded that by taking it for a model, and combining in a certain way media of different densities, telescopes might be constructed, by which

the images would have the same perfection, as when, in looking at objects, no other instrument is used than the eye itself.

891. Euler, conformably to the idea we have stated, endeavoured to ascertain the dimensions which object-glasses composed of glass and water ought to have, to imitate the combination that naturally takes place with respect to the eye; but Dollond rejected these dimensions, conceiving them to be founded on a law of refraction, the truth of which he doubted*; and he endeavoured to employ a different principle, but for some time without success. The dispute was carried on with warmth on both sides. Euler strenuously insisted on the possibility of destroying the diffusion of the focus in the way he had pointed out; and Dollond equally affirmed that it was impracticable, repelling every argument that was brought against him with the name and authority of Newton.

892. What rendered this celebrated artist so firm in his opinion, was the result of an experiment of Newton, which we have already mentioned (817), and respecting which he could not suppose a philosopher, who had been accustomed to interrogate Nature so closely, to be mistaken.

Newton having caused a pencil of light to pass through two contiguous media of different densities, viz. glass and water, remarked, he thought, that when the two surfaces, of which one received the incident rays, and the other gave issue to the emergent rays, were so disposed that the light was restored to its due progress by contrary refractions, so that the emergent rays became parallel to the incident rays, it always came out white. On the contrary, if the emergent rays were inclined to the incident rays, the whiteness of the light, in proportion as it removed from the point of emergence, became coloured towards its extremities *.

---

* Smith's Treatise on Optics, p. 384, note 661.

893. Now observe the consequence that followed from this result, which Newton extended by analogy to every kind of medium. The object-glasses which are employed in the construction of telescopes only produce the images which become the objects of vision (873) to an eye placed behind the eye-glass, so far as refraction through these object-glasses removes the emergent rays, relative to each pencil of light, from their parallelism with the incident rays. Therefore, since where this parallelism ceases to take place we cannot prevent the colours contained in the light from separating, even when we attempt to combine substances differently refringent, it is impossible to reconcile the destruction of the rainbow-coloured fringes which border the images, with the tendency of refraction to produce these same images. This consequence will appear still more evident from some new details into which we shall presently enter.

The persuasion that Newton had made his experiments with his usual acuracy, and the researches of Clairault, who, having examined the law proposed by Euler, found that it would not stand the test of calculation, led to the belief that Newton had fixed the bounds which science and art were unable to overleap.

894. Nevertheless, in 1755, Klingenstiern, mathetical professor at Upsal, sent a paper to Dollond, in which, though he confined himself in his arguments to metaphysics and geometry, he combated the experiment so forcibly, that Dollond could not help doubting its truth. At length he ventured to repeat it, and found it to be false. He joined two glass

---

* Optice Lucis, lib. i, pars 2, experim. 8.

plates by two of their edges, in such manner that he could vary the angle which they formed at pleasure, and then filled the intermediate space with water. In this water he immersed a glass prism, with its angle upwards, that is, in a contrary sense to the angle formed by the two plates of glass. Afterwards he inclined these plates in different degrees, till the objects seen through this double prism were apparently at the same height as in simple vision. He was then sure that the refractions destroyed one another, that is, that the emergent rays were parallel to the incident rays. Now the images in this case were tinged with the colours of the rainbow. Then if the glass plates were moved anew to a certain degree of inclination, the iris would disappear, but the objects were no longer at the same height as when they were seen directly; and thus the aberration of refrangibility was destroyed, while the refractions did not correct one another *.

This experiment decided the question. Substances were sought after whose combination was calculated to destroy the diffusion of foci, by permitting the greatest possible quantity of refraction to subsist. Geometricians of celebrity studied to ascertain the best curves for object-glasses composed of different media; and to their combined researches we owe the construction of *achromatic* telescopes, that is to say, of those which represent the images terminated distinctly, without any fringe of borrowed colours. We shall explain as clearly as we can the principles on which this construction is founded.

895. We have seen (689) that Newton ascertained directly the difference between the sines of refraction of the differently coloured rays which compose light,

---

* Smith's Treatise on Optics, p. 383, notes 658 *& seq.*

in the instance of its passing from glass into air, and found that the law of this difference was the same as that which represents the seven notes of our musical scale, in the minor mood. Let us suppose a prism to be used of a different substance from glass, and much denser, for example. If the circumstances are the same, that is to say, if the two refringent angles are equal, and the incident rays equally inclined to the refringent surfaces, these rays will be inflected in general under larger angles in the second prism; whence it follows, that the beam will be dilated in a greater degree on coming out of that prism. Let us further suppose the partial refractions to follow one and the same law with respect to all kinds of substances, that is, the law represented by the musical scale. If we take for the term of comparison the refraction of the ray that occupies the middle of the solar spectrum, and consider it as the axis of the dilated beam, it is evident that the total quantity of dilatation will follow, for the different substances, the same proportion as the refraction of the ray in question; so that if the refraction of that ray be one-third greater in the second prism, the beam that comes out of it will be proportionably dilated in a wider angle. The refraction of the ray in this case that occupies the middle of the spectrum, is denominated the *mean refraction,* and the quantity of dilatation, or excess of refraction of the violent ray over the red ray, is called *dispersion.*

In the same hypothesis, where the mean refraction shall be proportional to the dispersion, we can never annihilate the effect of the dispersion by the use of several media, without destroying the effect of the mean refraction at the same time: for the compensation that would take place with regard to the axis of the beam would equally extend to all the other rays, that should come out in like manner parallel to their first directions. Such was the consequence to which Newton's experiment led, and which he himself derived from it.

This however is not the case; for the law which the refractions of the differently coloured rays observe varies according to the different nature of the media, or, which amounts to the same thing, the dispersion is not proportional, in the different media, to the mean refraction; so that it may happen, for example, that a medium which should have a mean refraction a little stronger only than that of another medium, might occasion to the rays of light a much greater degree of dispersion.

896. This being premised, let us conceive in the first place two equal and similar prisms of the same matter so applied to each other that their refringent angles are turned contrary ways. Let *a c b*, *c b y*, (fig. 156), be sections of the two prisms in a direction perpendicular to the axis; *c* and *b* will be the refringent angles. Now, in this case, it is evident that a beam of light, *d e*, which meets the surface, *c a*, under any degree of obliquity, after being dilated in passing through the two prisms, will come out in such manner that the different emergent rays *k s*, *r q*, *t u*, will be parallel to the incident ray *d e*, since *b y* is itself parallel to *c a*.

Let us next imagine that the prism *c b y*, being of a different nature from the prism *a c b*, has a mean refraction only a little stronger, and that at the same time the dispersion which it occasions to the rays is much greater in proportion: the axis, *r q*, of the emergent pencil will be no longer directed by the mean refraction parallel to *d e;* and of consequence the image of the point *d* will be a little displaced. Moreover, the extreme rays, *k s*, *t u*, will diverge by a much greater quantity than that which measures the deviation of the image from the point *d*. If we then vary the angle *c b y* as far as the point where the image would be restored to its place, and where in consequence the effect of the mean refraction would be destroyed, it is evident that the dispersion will be still very perceptible. Lastly, if we continue to vary the same angle till the effect of the dispersion shall be destroyed in its turn, the mean refraction will reappear, and the image of the point *d* will be displaced anew: that is to say, on the one hand the light will be recomposed, and on the other the emergent rays will depart from their state of parallelism with the incident rays.

897. Let us now call to mind the two principles already established: a lenticular glass is nothing else than an assemblage of small portions of prisms, the faces of which are confounded with that of the glass in places at which one and the same ray enters and comes out (885); and when the same glass receives, on one of its faces, rays transmitted from different points of an object, it produces an image of that object on the side of the opposite face solely in consequence of this, that the emergent rays are inclined with respect to the incident rays (893). We see then how it is possible to form an object-glass, by combining media of different densities, in such manner that the light shall issue from this glass without any dispersion, while the effect of refraction to produce the image of which we have spoken shall still subsist.

By means of this combination, the rays of each of the pencils of light that have passed through the object-glass direct themselves so as sensibly to meet in one and the same point of the axis of the pencil, and form there a joint focus, by the union of all the separate foci. Strictly speaking, there are none but the red rays and violet rays whose foci exactly coincide; but the small aberrations that exist in the intermediate rays are in a manner concealed by the perfect coincidence of the extremes.

898. The two substances of which the object-glass of achromatic telescopes are formed, are *flint glass*, which is a kind of glass that contains about a third of *minium* or red oxyd of lead, and *crown glass*, which is of the same nature as the glass commonly employed by glaziers. The dispersion produced by flint glass has been found to be much greater than that arising from crown glass, nearly in the proportion of three to two, while its mean refraction very little surpasses that of the other *. In a great number of achromatic telescopes the object-glass is formed simply of two glasses, one convex on one side and concave on the other, which is of flint glass, the other bi-convex, which is of crown glass, and has one of its convex sides fitted to the concave side of the first. Other telescopes have their object-glass composed of a bi-concave of flint glass placed between two bi-convex glasses of crown glass. The last of these are the most perfect *(n)*.

---

* According to the experiments of Clairault, the proportion of refraction for the mean ray is in flint glass that of 1·6 to 1, and in common glass that of 1·55 to 1. Smith's Optics, p. 447.

(n) Although foreigners in general urge their claims to the invention of the achromatic telescope, yet there is the most unquestionable evidence that such instrument was first invented and constructed about the year 1758 by Mr. John Dollond. The term *achromatic*, by which they are now distinguished, was first given to them by the late Dr. Bevis: though Lalande, in the 3d volume of Montucla's History of Mathematics, pa. 447, says, " Le mot *achromatique* vient du mot Grec *chroma*, couleur, et de l'*a* privatif de la même langue. M. de Lalande *nous paroit* être le premier auteur de cette heureuse denomination."

The subject of achromatic telescopes, however interesting and curious, cannot be fully treated in the space devoted to it in this Treatise. Those, therefore, who wish to acquaint themselves thoroughly with the nature and theory of this important improvement, may consult the papers by

899. The construction we have been describing corrects only the aberration of refrangibility with respect to the object-glass, that which proceeds from the eye-glass still subsisting; but as the short course which the rays that come from this glass have to traverse to reach the eye, permits them to undergo a very slight separation, the aberration that results from it is deemed of so little importance that it may be wholly neglected: the object-glass has effected the essential point; the rest is of a nature to be tolerated by the eye.

900. Having thus treated of instruments which enable the eye to surmount immense distances, we proceed to those which give magnitude to atoms. The microsope with two glasses has considerable analogy to the astronomical telescope (879). The object-glass, *g h* (fig. 157), is very small and very convex; the object, *a b*, is placed a little beyond the focus of this glass, whence it follows that the rays of each of the pencils that pass from *a* to *a'* and from *b* to *b'*, which rays would come out parallel if the object were exactly in the focus, are but little inclined to one another; so that they form a reversed image, *a' b'*, of the object, at a considerable distance from the object-glass, and which consequently is already of much greater extent than the object. The eye-glass *k n* is so situated

---

Dollond, *Maskelyne*, *Klingenstiern*, and others, in the *Philosoph. Transac.* vol. 50, et seq. *Euler*, in his *Dioptrics*, and in *Comment. Nov. Acad. Petropol. tom.* 18; *Clairault*, in *Mém. de l'Acad. Paris*, 1756, 1757, and 1762; *D'Alembert*, in *Mém. de l'Acad. Paris*, 1764; *Boscovich*, in the 1st vol. of his *Opera pertinentia ad Opticam*, &c.; *Blair*, in the 3d volume of the *Edinburgh Transac.*; *Rochon*, in *Journal de Physique*, year 9; or *Robison*, in the article TELESCOPE, *Encyclop. Britan.* Such as have not opportunities of referring to these voluminous works, may advantageously consult Mr. *Brewster's* additions to *Ferguson's Lectures*, vol ii, pa. 423—451, where there are some very useful tables and forms deduced from the investigations of Euler, Boscovich, and Robison.—TR.

that its focus concurs nearly with the middle, *x*, of the image *a' b'*, and thus the rays *l o*, *s y*, on the one part, and *t y*, *r o*, on the other, being very little divergent, and, besides, the two pencils to which these two rays belong acquiring on the contrary a considerable degree of convergence, the eye placed at *o* will see the object at *a'' b''* very much enlarged, for two distinct reasons.

For the image *a' b'*, if observed with the naked eye, would already appear sensibly larger than the object *a b*. Now that image becomes in its turn the object which the eye perceives through the eye-glass; and as this glass performs here the office of a powerful lens, the angle, *r o l*, in which the eye will see this same object distinctly in *a'' b''*, will be much greater than that under which it would see it with the same clearness without any intermediate aid. Therefore the magnitude of the image, being the result of two effects combined, of which one tends of itself very perceptibly to enlarge its dimensions, will increase in a very considerable proportion. There are microscopes also with three glasses, to which the preceding explanation may easily be applied.

These admirable instruments furnish us, if we may so express ourselves, with a double universe. They enable us to see, in almost imperceptible drops of different liquids, animals that were before unknown to us. In the organisation of plants they unveil many mysteries; to corpuscles that were seemingly without form, they give a regular figure; the dust which composes the seed of the mallows they convert into globules surrounded with projecting points; that which is conveyed from the stamina to the pistils of divers flowers, assumes in like manner a symmetrical form, that is invariably different in every different species; the smallest parts of insects exhibit an assemblage of members adapted to one another with an art of which ours is but a coarse imitation; and what the eye thus sees a second time is as new to it as that which it has not yet seen.

Brief Description of some particular Dioptrical Instruments.

The instruments we purpose to describe under this head are intended to represent images seen immediately on plane surfaces properly situated to receive them.

901. If in the window shutter of a chamber that is perfectly closed on all sides, a hole be made, about 27 millimetres, or an inch, in diameter, the light that enters at this orifice will delineate on the opposite wall the images of exterior objects, the traits of which are mere sketches, resembling slight shadows. The observation of this fact gave rise to the optical instrument known by the name of *camera obscura,* or *dark chamber.* Instead of leaving the opening, at which the light enters, free, a lenticular glass is applied to it, which causes the different pencils that flow from the exterior objects to form so many foci behind the glass, and at a distance from these foci a sheet of white paper is placed, on which the images are distinctly exhibited and invested with their natural colours. But these images are inverted, because the pencils intersect one another in passing through the lens. This is remedied by observing them reflected in a mirror situated horizontally or nearly so. If the camera obscura be in a frequented place we shall have a moving picture, in which all the objects will appear natural, or rather, we shall see a succession of scenes pleasantly varied.

902. There is a portable *camera obscura* in the form of a kind of square box, one of the lateral faces of which has a tube furnished with its lens. The images formed within are received by an inclined plane mirror, which reflects them to the top of the box, where they become visible on a glass, which has the outward surface roughened or unpolished, and serves as a lid to the box. To a spectator whose face is turned towards the objects these images are erect. This instrument has been constructed in different ways: it has been made in the form of a small pyramidal cabinet, in the upper part of which is the tube with its lens, which, in this case, has an horizontal position. The mirror is placed above, and always in an inclined position, which, to be as advantageous as possible, should form with the horizon an angle of 45 degrees. Here it is the mirror which receives the rays that flow immediately from the objects, and sends them to the lens; whereas in the preceding construction, the rays go from the lens to the mirror. The images are depicted on a sheet of white paper, placed horizontally at the bottom of the camera obscura; and are seen by means of a large aperture in one of the lateral faces, which is commonly ornamented with two small curtains, that the observer by having his head covered, may look through without suffering the light to pass.

If a second hole be made in the same part, large enough to admit the right arm, the camera obscura may be used for drawing landscapes or buildings, by tracing the pencil over the outlines of the images seen by the eye (o).

(o) Mr. Brewster, who has paid a long and successful attention to the theory and practice of Optics, has discovered that the principal causes of indistinctness in the camera obscura, may be removed, and the image

903. The magic-lantern, invented by Kircher, the name of which is become in a manner trite, by

rendered very brilliant and beautiful, by receiving it on a silvered glass, as the silvered back of a looking-glass; the small eminences on the surface so silvered being removed by grinding it carefully with a bed of hones. This gentleman has likewise, in his second edition of *Ferguson's Lectures*, described an ingenious portable camera obscura, invented by Mr. Thomson of Duddingston; and which is so contrived that it may be put together and carried like an umbrella.

The celebrated mechanic and philosopher, Dr. Hooke, had a contrivance by which he could exhibit the images of external objects in a *light* room, equally vivid and distinct with their images received in a dark room. This contrivance is mentioned, but not described, in *Birch's History of the Royal Society*: nor have we been able to meet with a description of it in any other work.

Dr. W. H. *Wollaston* has very recently invented a portable instrument for drawing in perspective, to which he has given the name of *camera lucida*: the following description of it was given in N°. 8, of the *Retrospect of Philosophical, &c. Discoveries*.

In this instrument two plane reflectors are fixed at such angles with regard to each other, that the objects intended to be delineated are seen after reflection from the second mirror, as though they were on the same plane as that whereon the paper is placed which is to contain the drawing. These plane reflectors may be either common mirrors with a silver coating at the back of each, or two contiguous faces of a glass prism, in which latter case the image will be produced by what is called prismatic reflection. In either case the most convenient position, in which the reflecting surfaces can be arranged, will be such as will cause the rays proceeding directly from the object and falling as incident rays upon the first surface, after reflection from thence to the second, to emerge from that second reflecting surface in angles of 90 degrees with the direction of the original incident rays: for in these circumstances vertical objects may be projected upon a horizontal plane; and the instrument will be adapted to drawing upon a horizontal surface. Now, if two plane mirrors are used, the incident rays upon the first will make right-angles with the emergent rays from the second, when those mirrors are fixed so as to make angles of either 45 or 135 degrees with each other. In this case the mirror which first receives the rays from the object may be entirely silvered at its back; but the second mirror is only to have a sufficient portion silvered to reflect the image of the proposed object to the eye; and thus to allow the paper, on which the drawing is to be made, to be seen either through an opening of the silvering or past the edges of the same, by one portion of the eye, while the double reflected object is seen in the silvering by the other portion of the same eye. When prismatic reflection is employed, the

the use that is made of this instrument to exhibit to the curiosity of the vulgar an appearance of necro-

prism must not be triangular as usually constructed, but quadrangular, and the two reflecting surfaces (to produce an angle of 90 degrees between the first incident and second emergent rays) must make an angle of 135 degrees, while the opposite angle must be one of 90 degrees, and the other two angles may be either respectively equal or unequal at pleasure: then one of the faces which make right-angles with each other is to be turned towards the object or objects to be delineated, and the rays after passing through that surface and reflection from the two next faces, will emerge from the fourth under the proposed angle.

The mirrors or other reflecting surfaces are mounted in a proper frame, and supported at a suitable distance from the paper intended to receive the drawing: and, when necessary, either a double concave or a double convex glass may be fixed in the frame and properly adjusted, to produce distinct vision when the apparatus is used by short-sighted or long-sighted persons respectively. These concave or convex glasses may conveniently be made of 12 inches focal length; the instrument must then be supported at the distance of 12 inches from the paper; a distance which is convenient enough in other respects.

Dr. Wollaston has himself published a description of this instrument, in *Nicholson's Philosophical Journal,* and *Tilloch's Philosophical Magazine;* where he likewise institutes a comparison between the camera obscura and the camera lucida.

The objections to the camera obscura are:

1st. That it is too large to be carried about with convenience.

The camera lucida is as small and portable as can be wished.

2dly. In the former, all objects that are not situated near the centre of mancy, is worthy the attention of those who know it to have no magical property. It consists of a tin or wooden box, with a lamp or large lighted candle in the middle of the bottom part. The rays thrown out by the flame are received by a lens, which collects them and makes them fall closer on a small plane glass, on which the different figures are drawn. The effect of this first lens is simply to throw light on the figures, which must be in an inverted position. Sometimes, instead of the lens, a concave mirror placed behind the light is used, and in some instruments the effects of the lens and mirror are combined. Before the plane glass is a second lens, in passing through which the pencils of light that flow from the different points of the figure intersect, while the refraction at the same time causes the rays of which each pencil is the assemblage to come out parallel. These rays then pass through a circular aperture made in a piece of paper properly situated, and fall on a third lens, which may be moved farther from or brought nearer to the second lens at pleasure, by a moveable tube to the end of which it is fixed.

The rays which have passed through this third lens produce on the opposite wall, or on a sheet placed against the wall, an enlarged copy of the figures traced on the plane glass; and it is manifest that this copy represents the objects erect, because the pencils of light cross one another in the second lens. Two circumstances contribute to render the colours of the images that are exhibited to the view of the spectator more vivid, videlicet, the strength of the light to which the plane glass is exposed, and the luminous circle formed by the emergent rays on the wall. (*p*).

(*p*) Philosophers, by modifying the construction and operation of the magic-lantern, have transformed it into an instrument capable of producing

904. The solar microscope in reality differs from the magic-lantern in this only, that it is enlightened by a solar ray admitted into a dark room through a plane mirror that reflects it horizontally. The rays pass through a lens fitted to the hole in the window shutter. To the bright light which comes from this lens a small white glass called the carrier *(porte-objet)*

---

a much more imposing effect, to which they have given the name of *Phantasmagoria.* Here the mechanism of the operation is concealed from the spectators, who have only before their eyes a skreen of gauze or gummed muslin posited vertically, which serves as the ground of a picture where the images are depicted by reason of the transparency. The apartment is deprived of all light except that which proceeds from an apparatus hid behind the skreen. At the moment when the operation commences, a spectre appears (as of a skeleton, the head of a celebrated person, &c.) at first extremely small, but which afterwards increases rapidly, and thus seems to advance at a great rate towards the spectators: and when the scene passes before them in a room representing a cave hung with black, a solemn silence being occasionally interrupted by mournful sounds from an appropriate musical instrument, it is not easy for an observer to defend himself from the impression of terror, at the sight of an object in itself formed to produce the illusion, and which finds in the imagination a place already prepared for the reception of phantoms.

The instrument placed behind the gauze skreen is in fact a peculiar construction of the magic-lantern : only in the former it is necessary that is presented, and on this glass small insects, the farina of a butterfly, or other transparent corpuscles, are placed.

A second lens, intended to produce the image, is lined on the side of the carrier with a thin plate of lead, that has a pin-hole in the middle. It is through this aperture that the streams of light from the different points of the object pass as they cross one another; and the advantage that results from the construction is this:

It is manifest that we may augment or diminish the dimensions of the images, and consequently make the spectre appear more or less near to the spectator, by separating farther, or by bringing nearer together, the two lenses; but then the focus of the diverging rays which proceed from the same point of the transparent body will be no longer upon the skreen: we must therefore cause the machine so to recede or approach that the two motions being duly combined the image may be distinctly formed.

These phantasmagoria are furnished with a great number of transparencies, in each of which several changes may be made by slackening their springs: thus we may change at every instant, the form, the magnitude, and the distance of the spectres, as they appear to the spectator.

What has been said hitherto relates only to the images of transparent figures. To obtain those of opaque bodies, first place the gauze and box, at the distance of about six feet one from the other, and adapt to the orifice of the box an apparatus of two tubes furnished with two bi-convex lenses: an opaque body, such, for example, as a medal, or a picture, is attached to a little support posited in the middle of the box; the lamp and its supply of air situated in one of the foremost corners of the box, illuminates that object, and the reflected rays crossing the lenses proceed till they trace the image upon the gauze, with an amplification which is in the ratio of the distances.

If the image be not distinct, we must infer that it is not at the focus; but it may be adjusted in three different ways: 1. By moving the box to or from the gauze; 2. By moving the object nearer to, or farther from, the lenses within the box; 3 By slowly moving the tubes to cause a variation in the distance between the lenses.

We have not been able to ascertain the first inventor of this apparatus, It was first exhibited in London by M. *Paul de Philipsthal*, who took out a patent in 1802; the specification of which is published in N°. 95, of the first series of the *Repertory of Arts and Manufactures*.—Tr.

The streams of light we are speaking of, approach nearly to simple rays or infinitely thin cylinders of light, by which they are adapted to give clear and distinct impressions on a plane placed at any distance; and though the smallness of the aperture permits but little light to pass, yet, as this light is strong, the images it produces have always considerable brightness and vivacity.

The plane which receives these images may be removed to the distance of three or four metres (10 or 12 feet), which enlarges their dimensions so prodigiously as to change the smallest insect into a frightful colossus. At a medium distance, however, the images have more distinctness and are better defined.

905. We have thus gone over one of the most fruitful branches of natural philosophy, and the one perhaps which it is most difficult to treat. The fluid and the organ contribute equally to render the subject complicated. The first, infinitely diversified in its nature, is modified also in a thousand ways by the variety of its motions. No phenomena exhibit more delicate successions of shades, and none require

their applications, and how wide is the difference between what the progress of the rays traced by geometry represents, and the sensation occasioned by the image which the rays themselves delineate on the bottom of the eye!

The theory of light is far from exhausted: for many questions connected with vision have not yet been completely resolved. There exist certain phenomena, as those which relate to electricity, to phosphorescence, &c. in which the influence of the luminous fluid has not, as yet, been explained: none have yet ascertained how far they may extend the analogy of that fluid and caloric: the problem of the double refraction, on which we have nothing hitherto but mere essays, waits for its perfect solution from a hand able to vanquish the great difficulties which it presents: and the properties which some very recent researches appear to have indicated relatively to the diversity of colours in the solar spectrum, require that this region of nature should be interrogated anew by experiments made with an extreme precision.

In short, if we consider the multitude of results to which geometricians, philosophers, and chemists, have been led by the study of light, and add to the remembrance of what has been already done the expectation of what may be done hereafter, we shall acknowledge that no subject affords more extensive or more interesting observations, than the fluid that acts on the organ by which we are enabled to survey the whole compass of nature.

FINIS.

[illegible]

[illegible]

INDEX.

The Roman figures refer to the pages of the Introduction, and the Arabic figures to the paragraphs of the Work,

A.

Aberration of refrangibility, cause of, 886. Simple mode of remedying it, 887. See *Telescope*, achromatic.

Aberration of sphericity, cause of, 883. Newton's opinion of the impossibility of destroying it, 884.

Aberration of the stars, an optical illusion, explained, 780, 782.

Aberration, amplitude of, explained, 827.

Acceleration of motion produced by gravity, 46 & *seq.*

Action at a distance, meaning of, in electricity, 414.

Aeolipole, explanation of the vessel so called, 236.

Affinity, in chemistry, meaning of the term, 51, 55, 662.

Air, proof of its impenetrability, 12. Was long considered as one of the four elements, 172. Services it renders us, 243. Of what composed, 244 & *seq.* Its specific gravity, 248. Its pressure discovered as the cause of the ascent of water in pumps, 249 & *seq.* Degree of its pressure on the body of a middle-sized man, 250. Inconvenience of a sudden diminution of its pressure, *ibid.* Experiments proving its elasticity, 254 & *seq.* Ratio in which it contracts itself when pressed, 256. Effects of pressure on, 257 & *seq.* Manner in which the pressure of this fluid combines with its elasticity in pumps, 261 & *seq.* Effects of the preceding combination, 267. Decreases in density according to its elevation, 269 & 270. Force of caloric to dilate and increase its elasticity, 278 & *seq.* Caloric, the cause of double currents of, in rooms with fire-places, 279. East wind explained in the same way, 280. Ratio of its increasing elasticity between two fixed temperatures, 282 & 287. Similar ratio observeable with several kinds of gas, 288. Attempts to ascertain its elevation, 333. Considered as the vehicle of sound. See *Sound.*

Air-balloons, or art of travelling in the air, means devised by the ancient philosophers respecting, 335. Plan of Montgolfier, 336. Contrivances of other aeronauts, 337. Use of balloons may be serviceable to the progress of the sciences, 338.

Air-bladder, in fish, its use, 68.

Air-pump described, 246.

Alcohol, impenetrability not the cause of its increase when mixed with water, 12. Inconvenience of using it in thermometers, 164. Rises less than water in capillary tubes, 185. Set on fire by an electric spark, 421.

Alloy, in the precious metals, moderates their ductility, 41. Increases their density, *ibid.* That in the crown of Hiero of Syracuse, how discovered, 57 & 60.

Amber, yellow, or electrum, 377 note.

Amplitude of aberration. See *Aberration.*

Angle of incidence of a ray of light, in reflection, 629; in refraction, 640.

Angle of reflection, 629.

Angle of refraction, 640.

Angle, refringent, of a prism, 673.

Angle, visual, how formed, 761.

Anomalies in the electrisation of certain bodies, 390.

Aperture of a telescope, 884.

Apparatus for electrical experiments by heat, 451.

Apparatus termed a *couronne de tasses*, 494.

Arc, animal, and excitatory. See *Electricity*, galvanic.

Are, unit of superficial measures, 75.

Areometer, different kinds of, 62 *& seq.*

Art of flying, not given to man, 334.

Atmosphere. See *Air*.. Its pressure, &c. 250, 269, 333.

Attraction, gravity often so called, 50. Its operation at small distances compared with gravity, 51 *& seq.*

Attraction and repulsion, those seemingly exhibited by small bodies floating near one another on the surface of water explained, 199, 201 *& seq.* Extent of the operation of these principles in nature, 662. In what they differ from the occult qualities of the ancients, *ibid.*

Attractions and repulsions, electrical. See *Electricity*.

Attractions and repulsions, magnetic. See *Magnetism*.

Aurora borealis, description of, 627. Opinions respecting its cause, 628. Seeming effect of on the needle of

that may be derived from, in topography, 277. The variations of, do not exactly accord with the various pressure of the atmosphere, 329.

Battery, electrical, effects of, with their explanation, 436 & 437.

Bell, vibration of, when struck, explained, 344.

Bells, electrical, effects of, explained, 409.

Birds, flight of, explained, 334.

Bismuth, after being melted undergoes crystallisation, 228.

Black, name given to bodies that absorb the light that reaches them, 713.

Borate of Magnesia. See *Magnesia*.

Brass, density of, &c. 12.

Breath of animals, why visible in cold weather, 505.

Bugle-horn, cause of the difference of tone in this instrument, 368.

Burning-glass, its effects, 867.

C.

Caloric, 112. Two opinions of its nature, 113. Its equilibrium, 115 *& seq.* Its tendency to produce a change of state in bodies, 132 *& seq.* Degrees in which different bodies are dilated by its action, 152. Mode of ascertaining those degrees, 153. Effects of, on Air. See *Air*.

Clocks, changes occasioned in the length of their pendulums by the variations of temperature, how remedied, 158.

Cold, consists in the privation of heat, 131. Experiment exhibiting a false appearance of reflected cold, 122.

Collecting plate, in electricity, what, 443.

Clouds, formation of, 525.

Cobalt, exhibits magnetic properties, 610.

Combustion, how explained by the ancients, 168. Its true cause, 169.

Compass, mariner's. See Magnetic needle.

Compass card, described, 320.

Condenser, in electricity, described, 440.

Conductor of an electrical machine, 383.

Conductors of electricity, certain bodies so called, 380.

Conductors, humid, used in Volta's pile, 482.

Congelation, variations occasioned by, in the bulk of water, 213. Maximum of density arising from, ascertained, 214. Causes to which the expansion of water by, may be ascribed, 218 & 219. Effects of the expansive force of congealed water, 220 *& seq.*

Contact, immediate, with respect to the moleculæ of bodies, how to be understood, 8.

Continuity, law of, 183 note.

Colours, what expressed by the word, 671.

Colours in light, 676. Experiments proving the different refrangibility of rays reflected by differently coloured objects, 677. Other experiments shewing that light is composed of an infinite number of rays differently refrangible, according to the shades of the different colours, which may be referred to seven, 678—684. New experiment confirming the preceding ones, 685. How the expressions, red rays, blue rays, violet rays, &c. are to be understood, 686. Proportion ascertained between the sines of incidence and refraction of the rays which determine the limits of the seven principal colours, 689. This proportion analogous to the numbers that represent our musical scale, *ibid.* The mixture of all colours forms white, 690. Singular experiment of Newton, proving this, 691. Opinion of those who admit but of three colours in light, ill founded, 692. Effects which the colours of objects seen through a prism represent, explained, 693.

Colours in objects, depend on the fitness of a body, to reflect one sort of ray more abundantly than the others, which it absorbs, 711. This depends on the tenuity of the particles of which the bodies are composed, 725 *& seq.* The colour of a body more vivid, in proportion as the moleculæ of that body are thin, 729. Cause of the difference between bodies the colours of which, viewed in different degrees of obliquity, are permanent, and those which, viewed in the same manner, exhibit changes of colour, 731. Colours produced by the mixture of liquors that have no colour, accounted for, 733. Colours of transparent bodies, 740. Coloured rings. See *Rings.* Colours of the rainbow. See *Rainbow.*

Colours, accidental, 779 note *f.*

Crown glass, a kind of glass of the nature of common glass, 898.

Crystal, rock, cause of the divers colours it exhibits, 750.

Crystalline of the eye, 753.

Crystallisation, what is meant by the term, 80.

Crystallisation of metals, explained, 228.

Crystals, what is meant by the term, 4. Primitive forms of, 87. Secondary forms of, *ibid.* Forms of the integrant moleculæ of, 89 *& seq.* Laws to which the structure of crystals of the secondary form is subjected, 97 *& seq.*

Cyanite. See *Disthene.*

Curves, magnetic, 557.

D.

Declination of the magnetic needle. See *Needle.*

Decrements, laws of, to which the

structure of crystals is subjected, determined, 97 *& seq.*

Density, what is meant by the term, 7.

Dew, explained, 305. Sometimes an image of the rainbow seen in it, 710.

Diamond, from its great refractive power, Newton supposed it to be a combustible substance, 669.

Diatonic scale, formation of, 359.

Dilatation of gases and vapours, proportion in which it takes place, from the term of thawing ice to that of boiling water, 287—289. Reason of the uniformity of the law it follows relative to different fluids, 290. Dilatation of gases by their mixture with vapours, how determined, 311—314.

Dioptrics, meaning of, 614. Progress of the science, 817.

Dispersion of light, meaning of the term, 895. Does not follow the ratio of mean refraction, in different media, *ibid.*

Dissolution of salt by water, 298 & 300. Of water by air, *ibid.*

Disthene, or cyanite, anomalies which this stone exhibits relative to electricity by friction, 390.

Divisibility, what is meant by the term, 13.

Division of bodies, experiments proving to what minuteness it may be carried, 16 *& seq.* Judicious notion of Newton relative to the limits

Eel, electrical, of Surinam, 516 & 518. Experiment by which Walsh drew a spark from it, 519.

Elastic bodies, 29. Return to their natural form how effected, 30, 32. Utility of, in the arts, 36.

Elastic fluids. See *Fluids.*

Elasticity, in what it consists, 29.

Electricity by friction, sketch of the progress of, 377 *& seq.* Division of bodies, relative to electricity, into conductors or analectrics, and non-conductors or idio-electrics, 380 & 381. Principles on which the electrical machine is founded, 383. What is meant in electricity by insulated bodies, 384. The hypothesis of two fluids, the combination of which form the electrical fluid, 386. The idea of two kinds of electricity, positive and negative, admitted by Franklin, 388. The action of these two kinds of electricity superseded by that of the resinous and vitreous fluids, *ibid.* Different results of friction between two idiolectric bodies, relative to the kind of electricity which each of them acquires, 390. Meaning of tension or electric density, 391. Experiments, proving that electric action follows the inverse ratio of the square of the distance, 392 & 393. Hence it results, that the whole fluid of a conducting body is diffused about its surface, 394. Manner in which the electric fluid

412. The repulsion of bodies electrised negatively, in the hypothesis of a single fluid, difficult to explain, 413. Inadmissible inference derived from that hypothesis, that the molecule of solid bodies repel at a distance, 414. Influence of points in drawing and throwing off the electrical fluid, 415 *& seq.* Electrical spark, 421. Electrical spark will set alcohol on fire, *ibid.* Effect of the electric pistol, 422. Effects of electricity in vacuum, 423. Electrical odour, 424. Leyden experiment, its discovery, 425. Explanation, 426 *& seq.*; the quantities of vitreous and resinous fluid that escape from the two surfaces of the phial, observe a geometrical progression, 428. Experiment of the magic pane or fulminating square, 434. Electrical charge by cascade, 435. Effects of electric batteries in destroying life, melting metals, &c. 436. Those effects explained, 437. Method of reconciling to the theory of the two fluids, certain phenomena apparently inconsistent with it, 438. Description, &c. of the electrophorus, 439; of the condenser, 440; of the electrometer, 441; of an instrument in which the effects of the electrometer and the condenser are combined, 443. Decomposition of water by electricity, 525.

Electricity by heat, 450 *& seq.* Apparatus for distinguishing the electric poles of bodies susceptible of this mode of electrisation, 451. Electrical phenomena of the tourmalin, 453. Relative position of the poles in the same bodies, and form of the parts in which these poles reside, 459. Effects of crystals of borate of magnesia which have eight poles, 460.

Electricity, galvanic, its origin, 462. Galvani's experiments on frogs, 464. Similar experiments by other philosophers, 467 *& seq.* Animal and excitatory arcs, meaning of the terms, 467. How the experiments on frogs were first understood, 474. Volta's theory, 478 *& seq.* The true principle of galvanic electricity first discovered by Volta, 479. Experiments in proof of the principle, 480—485. Volta's pile, and the law by which the quantity of the fluid in its different discs varies, 486—488. Difference between an insulated and non-insulated pile, 488—490. In what the true element of the pile consists, 492. Analogy of the tourmalin to a pile, 493. Apparatus termed a couronne des tasses, explained, 494. A principle similar to that of galvanic electricity hinted at by Newton, 495. Commotion produced by the pile, 497 & 498. This commotion increased in several ways, 499 & 500. Mode of charging a Leyden phial by the pile, 501. Attractions produced by the pile, 501. Sparks produced by touching the pile with wire, and the wire melted, 502. Comparison of the effects of two piles formed of the same number of discs, but of different diameters, 503—506. Effects of the pile with those of a strong electrical battery compared, 507. Different substances of which the pile may be formed, 509 & 510. Singular gradation which several metals placed one upon another exhibit, relative to their different states of electricity, 509. The organ of electrical fishes apparently similar in its structure to the arrangement of the materials that compose the pile, 521. See *Torpedo.* Decomposition of water by galvanic electricity, 522. The most natural explanation that has yet been given of this phenomenon, 524. Experiments, proving that the oxydation of the metalic discs of the pile has no perceptible influence in producing the electricity, 526. Parallel between galvanic and ordinary electricity, 529. Remarkable resemblance between the effects of the differently coloured rays, in optics, and those of the vitreous and resinous electricity of the pile, 750.

Electricity, natural, 444 *& seq.* Experiments, shewing the analogy between the electric fluid and the matter of thunder, 444 & 445. Effect of thunder-rods and mode of constructing them, 446. Proofs of the utility of those rods, 447. Effect of what is called in electricity the returning stroke, 448. This effect explained, *ibid.* and 449.

Electrometer described, 441. Combined with the condenser, 443.

Electrophorus described, 439.

Elements, specious reasons of the ancient philosophers for admitting but four, 172.

Evaporation, in what it consists, 296 *& seq.* In what it differs from vaporisation, 229 & 301. Its quantity proportioned to the magnitude of the surfaces in contact with the air, 302 & 303. Evaporation of ice, 304. Different phenomena respecting evaporation explained, 305. Evaporation increases the elasticity of the air, 307; and diminishes its specific gravity, 309. Origin of fountains proceeding from evaporation, 331 *& seq.*

Euclase, stone so called, remarkable for its brittleness and hardness, 28.

Exciter, use of, in discharging the Leyden phial, 434.

Explanation, to be satisfactory should be minute, xvii.

Extension, notion of, to what limited, 3.

Eye, admirable nature of, 752 & 783. Its structure described, 753.

Eye-glass, in optical instruments, 879. Is sometimes double and triple, 882.

F

Fogs, formation of, 325.

Force, or power, what is meant by, 18.

Force, coercitive, in idiolectric bodies, considered, 400: in magnetic bodies, 541.

Force, directing, of the magnetic needle, 544.

Force of torsion, in what it consists, 392.

Fountain of compression, effects of, 254.

Fountain, intermittent, 260.

Fountains, opinions respecting the manner in which they are produced, 330. Evaporation their true origin, 331 *& seq.*

Fragile bodies, 28.

Franc, value of, in the French metrical system, 79.

Friction, used to estimate the hardness of bodies, 26 & 28.

Frogs, the first idea of galvanic electricity derived from experiments on, 464 *& seq.* See *Electricity*, galvanic.

Frost, how injurious to vegetation, 222.

G.

Galvanism. See *Electricity*, galvanic.

Gamut. See *Sounds* compared.

Gas, method of ascertaining in what manner any species of, is dilated, to counteract it, 600. Solution of the problem of magnetising steel bars to saturation, without touching a magnet, 603. Magnetism of iron mines contained in the terrestrial globe. See *Mines* of iron.

Gnomonics, or art of making dials, on what principle founded, 625.

Gold, how divisible and capable of extension by the arts, 15. Rank it occupies in the order of metals, 39. Its ductility, how remedied, 41.

Gramme, or unit of weights, value of, 70 & 78.

Gravity, in what it consists, 42. Descartes' opinion of its cause, 43. Difference between, and weight, 44. Law of the acceleration of motion produced by it in bodies, 47.

Gravity, specific, in what it consists, 56. Principle on which its determination is founded, 57. Experiments on the manner of determining it, *ibid.*, 59, 62 *& seq.*

Gymnotus, a species of electrical fish, 518 & 519.

H.

Hail, formation of, 327. In what it differs from snow, *ibid.*

Hard bodies, 28.

Hardness, in what it consists, 26.

Harmonics, what meant by in the theory of sounds, 355.

Heat, what is meant by the word, 112. Capacity of, 116. Conducting faculty of, 117. Specific heat, 126 *& seq.* Mode of determining specific heat by caloric, 139. Latent heat, 137. Sensible heat, *ibid.* & 138.

Heights, method of measuring, by the barometer, 268 *& seq.*

Herborizations of certain stones, how produced, 198.

History, natural, object of, ii. Divided into three branches, *ibid.*

Horizontal moon. See *Moon*.

Humidity, in what it consists, 176.

Hydrogen, one of the principles of water, 172. Hydrogenous gas, use of, in the construction of balloons, 337.

Hydrophanous agate, porosity of, ascertained by experiment, 9. Cause of its transparency in water, 739.

Hygrometer, defined, 175. That of Saussure, 180; of Deluc, 181.

Hygrometry, its object, 175.

I.

Ice. See *Water*.

Images of objects. See *Vision*.

Illusions, optical, multiplicity of, 767. That of the apparent convergency of two rows of trees explained, 768. Explanation of other illusions, 770—772. Illusion of the larger appearance of the moon at the horizon than at the meridian, 774. Illusions that have their source in motion, 775 *& seq.* Illusion of the aberration of the stars, 780—782.

Impenetrability, what is meant by, 12.

Inclination of the magnetic needle. See *Needle*.

Inertiæ, true notion of, 23—25.

Infatuations of the magnetic needle, 586.

Inflection of light, from what it proceeds, 663—666.

Instruments, optical, the most remarkable described, 748—816; 851—904.

Instruments, wind, manner in which sound is formed in, 364 *& seq.*

Insulated bodies. See *Electricity*.

Iron, rank occupied by, in the order of metals, 39. The harder this metal, the greater the difficulty which the electric and magnetic fluids experience in moving in its pores, 541. See *Magnetism* and *Mines* of iron.

K.

Kilogramme, value of, in the new French measures, 78.

L.

Lead, rank of, in metals, 39. Use of its red oxyde in the fabrication of flint-glass employed for achromatic telescopes, 806.

Lens, or lenticular glass, focus of rays that fall parallel on, 646.

[illegible] 5.
[illegible] sity
[illegible] is in
[illegible] scale of
[illegible] ion of
[illegible] Effects
[illegible] termin-
[illegible] 620 &
[illegible] dimi-
[illegible] shadow,
[illegible] con-
[illegible] 626.
[illegible] determine
[illegible] be-
[illegible] caloric, 119—121,

Ascension of, in [illegible] [illegible]es, 1[illegible]
[illegible] in the new French [illegible], 77.
[illegible], idea of the ancients respecting, 530. Its polarity discovered, ibid. Advantages resulting from the discovery, [illegible]

M.

Magic-lantern described, 203.

Magnesia, borat of, electric poles of its crystals by heat, 460. Remarkable analogy between the position of these poles, and the form of the parts in which they reside, *ibid.*

Magnetism, 530 *& seq.* Limited nature of the knowledge of the ancients respecting, 531. Earliest theories for explaining its effects, 530. Magnetic fluid, though different from the electric fluid, is governed by the same laws, 534. The magnetic fluid considered as composed of two distinct fluids, 535. Those fluids denominated the *austral* fluid and *boreal* fluids why, 539. Singular results relative to the forces which act on a magnetised needle freely suspended, 513—545. Theory of those results, 597 & 598. Experiments proving that the action of the magnetic forces follow the inverse ratio of the square of the distance, ism, its effect but trifling when a single bar only is employed, 570. Method of double contact described, 571. Condition requisite for its action to have the greatest possible effect, 572. Process of Æpinus for employing it more advantageously, 573. Another method, adopted by Coulomb, which remedies the inconvenience of consequent points, *ibid.* How to obtain bars strongly magnetised, 574. How to magnetise the needle of a compass, *ibid.* Construction of artificial magnets, 575. Powerful effect of these magnets, *ibid.* What is meant by the armour of natural magnets, 576. Requisite thickness of the armour to produce the greatest effect, *ibid.* Experiments which seemingly prove all bodies to be susceptible of the magnetic virtue, 595.

Magnetism of the globe. See *Globe.* Of iron mines. See *Mines.*

Magnets, artificial. See *Magnetism.*

Magnitude, real & apparent, of an object, 761.

Mass, what is meant by, 7.

Measure, French, new system of, explained, 69—79.

Medium, what bodies so called, 640.

Mercury, earliest experiments on the congelation of, 225. Determination of the degree to which it answers, 226. Its advantage in thermometers, 164. Experiments, proving that it does not deviate from the law of capillary tubes, 193.

Meridian, magnetic, what is meant by, 544.

Metals, good conductors of heat, 117. When polished, reflect radiant caloric, 120. Crystallised by the cold that succeeds to fusion, 228. Are good conductors of electricity, 380.

Meteors, what bodies so called, 324. Aqueous vapours described, 325 *& seq.*

Metre, meaning of, in the new French system of measure, 69.

Mica, requisite thickness of a small plate of, to reflect pure blue, 727.

Micrometer. See *Addenda.*

Microscope, simple, effects of, 873—876. A glass globule or drop of water substituted for a lenticular glass, gives a simple microscope, 877.

Microscope, with two glasses, described, 900. Advantage of this instrument, *ibid.*

Microscope, solar, described, 904.

Minerals, augmentation of, how occasioned, 81. Difference of, from organic beings, *ibid.*

Mines of iron, reversion of the poles which detached pieces of, exhibit, explained, 605. Species of, as distinguished by Linnæus, 606. Experiments shewing that the ferruginous crystals produced by nature are true magnets, 607 *& seq.*

Minium, or red oxyd of lead, utility of, in making flint-glass, 898.

Mirror, general effects of, 783.

Mirror, concave, general effects of, 791. Caustics produced by, how, 795 & 796. Motion of the caustics in certain cases, explained, 797, 799. Cases in which the images are seen on this side of or beyond its surface, 800—806. Its use in constructing telescopes, 806. Its effect in setting on fire, melting, or vitrifying, bodies exposed to its focus, 807. Experiment, in which the united effects of two concave mirrors are shewn, 808. Several plane mirrors substituted for a concave one, 309. How the circumstance of Archimedes setting the Roman ships on fire, is to be understood, 810.

Mirror, cylindrical or conical, amusing effects of, 816.

Mirror, convex, caustics produced by, how, 811. General effects of, 812—815.

Mirror, plane, represents the images at the same distance behind its surface, as the object is on this side, 784 Represents the magnitude of the images in a similar manner, 785. Can see in it but a part of ourselves, the height of which will be double that of the mirror, 784. The distance of the eye from the mirror, and the height of the object and mirror, being known, we may easily ascertain at what distance from the mirror an object must be placed to be completely seen in a position parallel to that of the mirror, 788. Motion of the image double that of the mirror, 789. By inclining the visual ray, many images of the same object are perceived at once by means of a mirror, this effect explained, 791 & 792.

Mobility, what is meant by, 18.

Moleculæ, of what order those are which reflect or refract light, 726.

Molecule, elementary, of minerals, 90.

Moleculæ, integrant of crystals, 90 *& seq.*; subtractive, iii.

Moon, its apparent horizontal magnitude, 774.

Monsoons, periodical winds so called, 321.

Monochord, 354 note.

Motion, different kinds of, 19.

Muriate of silver, phenomena exhibited by, when exposed to different rays of decomposed light, 749.

Myope, nature of the shortsightedness so distinguished, 871. Its remedy, *ibid.* Habits of those afflicted with it, 872.

N.

Nature, in what sense to be understood, iii. Sentiments excited towards the Supreme Being by the contemplation of, iv.

Needle, magnetic, action of the ter-

O.

Object-glass in optical instruments, 879.

Odour, electric, 424.

Odours, prove to what degree matter is divisible, 14.

Opacity, causes of, 738.

Opal, reflections of light which it darts from its interior, explained, 730.

Optics, the science of direct light, 614.

Oscillations, small, of the different points of a cord that yields sound, 343; of a bell in the same case, 344; of the air, occasioned by those of sonorous bodies, 343. The consideration of, applied to the theory of the propagation of sound, 364 *& seq.* The successive circles on the surface of water, on stones being thrown into it, occasioned by, 375.

Oxydation, that occasioned by the discs of Volta's pile, has no perceptible share in producing electricity, 526.

Oxygen, one of the principles of water, 172.

Oxygen gas, one of the principles of air, 244.

P.

we have followed in the distribution of the particular subjects belonging to it, vii.

Pile, Volta's. See *Electricity*, galvanic.

Platinum, the densest of known metals, 61. Advantage of, in the construction of telescopes, 806.

Point of emergence and of immersion; in optics, what, 640.

Points, use of, in supporting or throwing off the electric fluid, 415.

Points, cardinal, 3.0.

Points, consequent, of a magnet, 565. Of certain electric bodies by heat, 568.

Poles, electric, 451: magnetic, 539.

Porosity, meaning of, in bodies, 7. Proof of, 8 & 9.

Potteries, inconvenience resulting from the substance fabricated in, 156.

Power, or force, meaning of, 18.

Power, refractive, mode of determining, 667. Varies in bodies according to their densities, 668.

Presbytæ, defective sight of persons so called, 866. Remedy for the defect, *ibid.*

Prism, destined to unveil the true theory of colours, 672. Position in which the image of the solar spectrum produced by, becomes stationary, 675.

Propagation of light. See *Light*. Of sound. See *Sound*.

Properties, the most general, of bodies, 2—17.

Properties relative to certain forces soliciting or impelling bodies, 18—169.

Pumps, 261 & *seq.* Lifting-pumps, 262 & 263. Sucking-pumps, 264. Method of remedying an inconvenience to which they are subject, *ibid.* Forcing-pumps, 265.

Q.

Qualities, occult, of the ancients, moderns accused unjustly of reviving them, 662.

Quantity of motion, what meant by, 22.

R.

Rain, circumstances that determine it, 325.

Rainbow, description of, 694. Two often seen, an inner one and an outward one, *ibid.* The inner one explained, 696, 701 & 702. Explanation of the outward one, 699 & 703. Breadth of the two bows and cause of their increase, 704 & 705. Circumstances which occasion a greater or less part of a bow to be seen, 706. A third bow sometimes seen, 708. A number of other bows that cannot be seen, supposed possible by theory, *ibid.* Experiment by which Antonio de Dominis represented a rainbow, 709. Artificial imitation of a rainbow by throwing water into the air, 710. Copies of the rainbow in different objects, *ibid.* Solution of a difficulty respecting the outward bow, from fits of easy reflection and easy transmission, 735 & 736.

Ray, meaning of, in each of the two hypotheses of the propagation of light, 615. Ordinary ray, relative to double refraction, 827.

Rays, calorific, 747 & *seq.*; efficacious, 697 & 699; sonorous, 348.

Reflection of light, angle of, equal to the angle of incidence, 629. Effects of, against a plane surface, 630 & 631; against a concave and spherical surface, 632—636; against a convex and spherical surface, 638 & 639. Relation between reflection and refraction, 647—649. Reasons for believing that reflection depends on a certain force diffused uniformly over the surface of bodies, and that acts at a small distance, 652—655.

Refraction of light, 640. So takes place, in the same medium, that the sine of its angle is always proportional to that of the angle of incidence, 641. Law of, sought in vain by Kepler, 817; discovered by Snellius, *ibid.* Descartes substituted for the proportion of the cosecants that of the sines, *ibid.* Effects of in mediums terminated by a convex surface, 642—644; by a concave surface, 645. Relation between refraction and reflection. 647—649. Refraction explained by means of attraction at small distances, 656 & 657. Constant proportion between the sines of incidence and refraction demonstrated, 657 note. Refraction greater in combustible bodies than in non-combustible bodies of the same density. See *Power*, refractive.

Refraction, double, discovery of, 824. Difficulties attending the theory of, *ibid*. General effects of, when one or two rhomboids of carbonate of lime are used, 826—833. Explanation of a phenomenon respecting, that disappoints the expectation of the observer, 834. Experiment respecting, in which are seen at pleasure two or four images of the same point through two rhomboids, 835. Huyghens' theory of, 836. Newton's theory of, *ibid*. Theory of other philosophers, who supposed they could bring the second refraction, under the ordinary laws, 838. Difficulty of reconciling this theory with observations, 840. Correction to be made in the law proposed by Newton, 842—847. The circumstance of one of the two images seen through a rhomboid appearing farther from the eye than the other, explained, 848. Particulars of the double refraction of different na-

of two intermediate ones, where the colours were obscure, 716. Other rings seen by refraction, 718. Phenomenon of the coloured rings analysed, 721 & 722. Consequences derived by Newton from his observations on the subject, 725 *& seq.*

S.

Salt, sea, its extraction favoured by previous evaporation, 302.

Sciences, grand divisions of, i. Points in which several nearly meet, ii.

Shadow, a privation of light, 619. On what the form of, depends, 619—625. Its use in ascertaining the height of a tower, 625 note.

Shock, electric, by the Leyden phial, 425; by Volta's pile, 497 & 498. Difference between them, 505. See *Electricity*.

Silver, rarefaction of, when mixed with copper, 12. Rank of, in metals, 39.

Silurus, fish so called, electrical property of, 518.

Snow, how formed, 326.

Soft bodies, 28.

Solidity, meaning of, 6.

Solution, of salt by water, 298 & 300; of water by air, 299 & 300.

Sonometer, an instrument used for determining sounds, 354.

Sound, air the vehicle of, 340. Printime, 354. Relation between the number of vibrations that answer to the intervals of sound in the musical scale, *ibid.* Triple resonance of a sonorous cord, 355. The three sounds which such cord makes are the first terms of an infinite series of harmonics, *ibid.* Tartini's experiment respecting a triple resonance, 357. Another experiment, in which the two parts of a cord, divided by a slight obstacle, subdivide themselves into several equal portions, 358. Formation of the ordinary gamut, from the triple resonance of a vibrating cord, 359. Preference of this gamut over that which is comprised in the series of harmonics of a sonorous cord, 360. Necessity of altering, by what is called *temperament*, the thirds and fifths in the concord of stringed instruments, 363.

Spar, Icelandic, name given to transparent rhomboids of carbonate of lime, 824.

Spectacles for reading, discovery of, 817. Effects of, 866.

Spectrum, solar, or coloured image of the sun, produced by light that has passed through a prism, 678. Difference in the rays that compose it, relative to their calorific qualities, 743 & 747. Differences in the same rays, relative to their luminous quality, 748. Other differences relative to the property of favouring oxydation or disoxygenation, 749. See further, *Colours* in light.

Spring of a watch, diminution of its force while it unbends itself, remedied, 36.

Springs, utility of, 36.

Square, magic or fulminating, 434.

Steel, receives the magnetic virtue with difficulty, but retains it long, 569.

Steam-engines, effects of, explained, 239 *& seq.*

Stere, value of, in the new French measures, 76.

Sweat, or sensible perspiration, 10.

Syphon, effects of, to what ascribable, 266.

System, different acceptations of the word, vi & vii. Difference between, and theory, vii.

System of the new French measures, account of, 73 *& seq.*

T.

Telescope, on what the effects of, depend, 878. Achromatic telescope, account of its discovery, 890—895; its effect, 894; principle on which its construction is founded, 895—897; manner in which its object-glass is formed, 898. Astronomical telescope described, 879. Batavian telescope, 880; Gregorian, 889; Newtonian, 888. Dioptric telescopes, 883; catadioptric, 888.

Temperament, relative to sounds. See *Sounds.*

Tension, electric, 391.

Theory, meaning of, and how it contributes to the progress of the sciences, v *& seq.* Details the touchstone of, xvii.

Thermometer, general description of, 114. Origin of, 160. The one called centigrade, 163. Construction of the common one, *ibid.* Advantage of mercury in the construction of, 164. That of Amontons described, 284. Centigrade, 163. Delisle's, 167. Farenheit's, 166. Reaumur's, 162. Leslie's, 167 note.

Thunder-rods, construction and advantageous effects of, 446 *& seq.*

Time, how to be considered in estimating velocity, 21. Proportion between, and space, in the accelerated motion arising from gravity, 47.

Topaz, singular one, of which the extremities were analogous to those of magnetic bodies, 568.

Torpedo, its electrical organ described, 513. Opinion of the ancients respecting the shock it gives on being touched, 515 & 516. Experiments proving the shock to arise from electricity, 517 *& seq.* Walsh's opinion of the manner in which the fluid acts in the shock, 521. Substances that compose the organ arranged, according to Volta, like those which form the pile, *ibid.*

Torrents, cause of, 331.

Torsion, force of, 393.

Touch, manner in which it enables the eye to judge of the form, magnitude, and distance, of objects 756.

Tourmalin, electric virtue it acquires by heat, 452. Its action on light bodies to which one of its poles is presented, 453. How the two electric fluids are distributed in it, 454. Paradox which its manner of acting on an electrised silk thread exhibits, explained, 455. Reciprocal action of two tourmalins, 456. Variations in the effects of a tourmalin according to its degree of heat, 457. The broken pieces of a tourmalin having two poles like a whole tourmalin, explained, 458. Affinity between the forms of the two summits of a tourmalin and the position of the electric poles, 459. Comparison of a tourmalin electrised by heat, with Volta's pile, 493. Connection of magnetism with electricity derived from the tourmalin, 535.

Tremery, apparent inconsistency in electricity solved by, 438.

Tubes, capillary, phenomena they present, explained, 183 *& seq.* Circumstance in which water rises in them above its level by forming an hyperbola, 196. Different effects to which the cause of water rising in capillary tubes is ascribable, explained, 198 *& seq.* Theory of Laplace, 197 note.

U.

Unit of time, employed in the case of

rives from the touch, 756 & 757. Why objects appear to us right, though their images are reversed, 757. Why objects are not seen double, though their image is in each eye, 760. How the impression of distance combines with that of apparent magnitude, to produce the sensation of the real magnitude, 762. Circumstances that deceive us in estimating the real magnitude of objects, 763. How, when between us and an object other objects intervene, we are thereby better enabled to estimate the distance of that object, 765. Defect of vision when the eye first admits light exemplified from the operation of the cataract, 766. Various instances of illusion to which vision is subject, 767 *& seq.* See *Illusions.* Vision aided by art, 783. See further, *Lens*, *Spectacles*, *Microscope*, and *Telescope*.

Volume of a body, what is meant by, 6.

W.

Water, physical properties of, in a state of liquidity, 170. Uses of, 171. Was long regarded as an element, 172. Its composition, *ibid.* Is sensibly incompressible, 174. Discovered by Newton to have an inflammable principle, 670. Decomposed by galvanic electricity, 522;

the new French system of measures, 69 *& seq.*

Windows, glass, why wetted within in frosty weather, and without when it thaws, 305.

Winds, general cause of, 318. Velocity of, 319. Utility of, 322 & 323. East wind explained, 280. Division of winds into general, periodical, and irregular, with their several explanations, 321.

Wings of birds, their manner of use, 334.

Z.

Zinc, density of, augmented when mixed with copper, 12. When insulated acquires vitreous electricity by friction, 390.

Zones of no declination, 581.

[illegible]

[illegible]

ADDENDA ET CORRIGENDA.

VOL. I.

PA. 25, note *a*, line 6 from bottom: for—late Professor of Chemistry at Woolwich; read—late Professor of Anatomy and Surgery, Leicester-square, London.

Pa. 36, line 10, from bottom: for—are about to lay down; read—have just said.

Pa. 49, line 2: for—We have; read—46. We have.

Pa. 53, par 51. In the new edition of M. Haüy's Treatise, he has considerably expanded the ideas suggested in this paragraph, and has at the same time introduced a brief view of the principles of Chemical Statics. The manner in which he has now treated these subjects, is as follows:

The attraction which solicits the bodies of our planetary system to tend towards the sun and towards each other, does not differ from that which occasions the descent of bodies placed near the earth. These latter bodies have also a tendency to approach one towards an other in virtue of the same force; but the effect is destroyed by the much more energetic attraction that the earth exercises upon them. If we suppose a series of bodies whose volumes are continually diminishing, we might be led to infer that their mutual tendency ought always to deviate farther from the term at which they would commence to be comparable with the terrestrial attraction.

Yet the *moleculæ* of solid bodies placed at the extremity of this series, are as it were enchained the one to the other by a powerful action; and it is known to what a high degree several of these bodies resist the efforts that are made to divide them. This consideration, joined to others that are mentioned in the course of the present work, has given birth to the idea of a new species of attraction, on which depends the cohesion of those moleculæ, and which is distinguished from gravitation in this particular that it acts only at or very near contact, and is evanescent at the least sensible distance from contact. The attraction under consideration has received the names of *affinity*, and *molecular attraction*.

Strictly speaking, the action of affinity is extended indefinitely about each molecule. But as it diminishes very rapidly, so that beyond a very small distance it ceases to be appreciable; we regard it as nothing at that term, and call the *sphere of sensible activity* that whose centre is confounded with that of the particle and whose radius is equal to the distance of which we have spoken.

A very simple observation may enable us to understand the manner of action of this force. It is this: a small fragment separated from a mass of metal or of stone, does not less resist the effort of the file to detach its particles, than when this fragment was united to the body; whence we may see that all the rest of the mass had no influence upon the force with which the particles of the fragment adhered to one another.

Various interesting experiments scatter fresh light upon this conclusion. If we take two plates of marble, or well-polished plates of glass, and cause them to glide one over another so that they may touch the most exactly possible, we shall observe that they adhere strongly one to the other. Each of the two surfaces having, in this case, a great number of points which are brought into contact with the corresponding points of the other surface, or being only separated by a distance extremely small, there will result a sum of attractions in some measure comparable to that which holds together two parts of one and the same body distinguished by an imaginary plane. The pressure of the ambient air, to which one might at first be tempted to attribute the adherence of the two bodies, does nothing more than augment the effect of the attraction. For if these bodies be placed in the vacuum of an air-pump, they will still continue to adhere together with a force which will be merely diminished by a quantity equal to the action of the air. It has been remarked, that the same bodies after having remained for some time in contact, have opposed more resistance to their separation than at the first moment. Hence it would seem that the prolonged action of the attractive force solicits the moleculæ to little oscillations, by reason of which the projecting parts of each surface place themselves in of all the moleculæ in contact, in such manner that, to cause the separation, all these attractions must be overcome by a single effort. In the second case, on the contrary, the separation is made, so to speak, in detail, by successive actions, each of which deprives but a small part of the moleculæ of the attractive force.

The spherical figure assumed by the drops of water and of mercury, and which obtain in a vacuum, present a new proof of the effects of molecular attraction. This figure is the more exact as the drop is smaller, and as the plane which sustains it acts less upon it by its particular attraction. Thus the dew forms upon the leaves of certain plants globules which only touch by a point. But the drops which are found upon glass and different stones are merely hemispherical; and as the reciprocal attraction of aqueous moleculæ is considerably weakened by the action of another cause, if the drop which is in the situation we are speaking of has a certain volume, gravity will make it assume the form of a semi-spheroid whose minor axis is in a vertical position. If, on the contrary, the drop hang from the inferior surface of the body, it will be so lengthened that the major axis of the spheroid will be situated vertically.

If we cause two drops of water or of mercury to advance gently one towards the other, till they are very near, they will be seen to dart towards each other and unite into a single drop.

But the effects of this force exhibit themselves nowhere in a manner so evident, and at the same time so admirable, as in those varied operations where chemistry, placing the elements of bodies as it were in contest with one another, creates again that which it had destroyed, or transforms it into a being entirely new; and, by successive decompositions and combinations, obtains results which are so many faithful imitations of those of nature, while of others nature furnishes no model.

The Equilibrium between the Affinities of the Principles which form Neutral Combinations.

Though the developement of the phenomena that depend upon the actions exerted by the elementary moleculæ of bodies one upon another does not enter into our plan, the point of view under which we shall now contemplate them is not foreign to Physics, since it enables us to perceive the generality of the laws to which those phenomena are subjected.

In the mutual combination of an acid with an alkali, if it be supposed that the quantity of alkali, at first very small, augments progressively with regard to the quantity of acid, there will be a term where the properties of the two principles will disappear, in such manner, for example, that if the salt which results from the combination is soluble, a blue vegetable tincture, brought into contact with the solution, will not undergo any alteration. It is then said that the combination is in the *neutral state*.

The word *saturation* is employed to indicate the term where, the reciprocal affinities of the two principles being satisfied, neither of them is more susceptible of combining with a new quantity of the other. Now this term does not correspond with that which constitutes the neutral state. We shall endeavour to elucidate the distinction by adopting the ideas of the celebrated Laplace.

When an acid is combined with an alkali, we may conceive the moleculæ of the acid as acting by their centres of action, upon the moleculæ of the alkali reunited about them, in such manner as to form so many little spheres whose centres shall be occupied by that acid; and the combination of the two principles will be that which gives the point of saturation, if the alkali is in the required proportion, so that the radius of each sphere shall be equal to that of the sphere of sensible affinity of the acid with respect to the alkali. We may substitute for this hypothesis, that where the little spheres shall be composed of moleculæ of the acid and shall have their centres occupied by the alkali. That there may be saturation, it is still necessary that the radius of each little sphere be equal to that of the sphere of sensible affinity of the alkali for the acid; and it is obvious that the relative quantities of acid and alkali will be the same as in the preceding case; each hypothesis being only an equivalent manner of conceiving the reciprocal actions of the two principles which form the combination.

Let us now imagine that, the centres of the little spheres being occupied by the alkali, a blue vegetable tincture is put into contact with the salt, and that it remains without alteration. The coloured moleculæ are susceptible of acting by affinity, either upon the acid, or upon the alkali; and, since, in the present case, this affinity does not produce any effect, if we limit ourselves to consider it with regard to the acid, we shall conclude that it is in equilibrio with that which the alkali exercises upon the parts of that acid which compose the exterior stratum of the little sphere, or that with which the blue moleculæ are in contact. The salt is then in causes blue vegetable tinctures to pass to a red, because the quantity of acid relatively to that of the alkali, goes beyond the term which constitutes the neutral state, and approaches the limit which answers to saturation. Salts which are in this case have received the name of *salts with excess of acid*, or *acidulated salts.*

What has been said of an alkali may be extended generally to all the bases susceptible of combining with acids. There are salts likewise in which it is, on the contrary, the quantity of alkali which, relatively to the quantity of acid, goes beyond the point determining the neutral state, in such sort that their action transforms blue vegetable tinctures into green. These substances are called by the chemists, *salts with excess of alkali*, or *alkalized salts.* Of this number are, the borate of soda, vulgarly borax, and the carbonate of soda.

This method of representing the results of the combinations produced by acids and alkalis, conduces to explain that which happens to two neutral salts which, mixed the one with the other, exchange their bases, so that the new products which arise from this operation are still in the neutral state. The agreement which exists, in this respect, between theory and experience, serves to unveil a very remarkable property of affinity, namely, that the law to which its action is subjected, with regard to the distance, is the same for all bodies; so that the differences between the action of these bodies depend only upon the greater or less intensity of the particular affinity of each of them.

To elucidate this by a very simple example, let us imagine a particle of sulphuric acid lodged at the centre of a little sphere composed of any alkali whatever, in such manner that there shall be saturation, and let us denote by a the quantity of that alkali. Let us now substitute the muriatic acid for the sulphuric acid, and suppose that the action of the former is once less intense than that of the second. That the muriatic acid may saturate the same quantity, a, of alkali, it will be necessary, in the hypothesis where the law relative to the distance should be the same on both parts, that the particle of this acid, placed at the centre of the little sphere, shall have a mass double to that of the particle of sulphuric acid which it has replaced. Suppose, on the other hand, that this latter particle is capable of saturating a quantity of lime equal to $2a$. We shall hence conclude that the same quantity, $2a$, of lime is necessary to saturate the particle of muriatic acid. For, since the sulphuric acid is capable of acting until saturation upon two spheres composed the one of a of alkali, the other of $2a$ of lime, and the muriatic acid is in the requisite proportion to saturate the sphere composed of a of alkali, it is right that its action upon the sphere composed of $2a$ of lime, should still attain the term of saturation, as a consequence of this that the function of the distance being the same on both parts, the limits of the action are also the same.

We may suppose that the quantity, a, of alkali and the quantity, $2a$, of lime, inferior to that which the saturation requires, were solely sufficient to bring the sulphuric acid, for example, to the neutral state; in this case, the union of the same quantities with the muriatic acid will again determine the neutral state in an equal degree, that is to say, the radii of the little spheres whose centres we suppose occupied by the two acids, will differ by the same quantity from the radii of the spheres of sensible activity of the same acids upon the alkali and the lime.

According to this theory, if there be mixed together two neutral salts which may have the conditions necessary to produce an exchange of their bases, as obtains with regard to muriate of barytes, and sulphate of soda; the new salts which will result from this mixture, and which, in the present instance, will be sulphate of barytes, and muriate of soda, will be found in their turns in the neutral state. For if the first two salts are in such a ratio, that the quantity of barytes, for example, contained in the muriate of barytes, shall be that which is required to neutralise the quantity of sulphuric acid which contains the other salt, the quantity of soda comprised in this latter, will be also that which is capable of neutralising the quantity of muriatic acid which the muriate of barytes contains. If, on the contrary, one of the two salts, as the sulphate of soda, is in too great a proportion, there will only be decomposed the part necessary that the products of the operation may attain the degree which answers to the neutral state. The surplus will remain separate or foreign from the combination, by retaining its primitive state, without any portion of acid or of the base being set at liberty.

We have already observed this correlation between the affinities in the mixture of different neutral salts. But the respective quantities of base and of acid which several chemists have assigned for the same salts, do not accord with those which the permanence of the neutral state requires; as has been proved in a luminous discussion by the celebrated Guyton, who the neutral state: thus the mixture of nitrate of silver with muriate of potash or of soda determines a precipitate of muriate of silver, and all remains as before in the neutral state.

Pa. 55, par. 54. The reasoning in this paragraph is dilated and made more palpable by M. Haüy in the new edition of his work. But instead of quoting the additional exemplification of his view of the subject, the Translator avails himself of this opportunity to state the opinion of M. Libes as given in his *Nouveau Dictionnaire de Physique.* This philosopher endeavours to reduce the molecular attraction to the laws of universal attraction, and to shew the probability that Newton was right when he suggested that one attraction might be the cause of all the chemical attractions. To shew that two elementary moleculæ in contact ought to exert upon one another an infinite action, while the law of attraction is directly as the masses and inversely as the square of the distances, the reasoning of M. Libes is simply this: If the masses of two finite bodies which attract each other, were to become infinitely small, the attraction which they would exercise the one upon the other, would experience, in respect of the masses, an infinite diminution. But if those masses, thus become infinitely small, are in contact, their centres will be found infinitely near to one another; consequently, the attraction, which follows the inverse ratio of the squares of the distances, having augmented infinitely more with regard to the approach of the centres of action, than it has diminished by reason of the extreme minuteness of the masses, the result must be an infinite attraction.

Pa. 104, par. 114. M. Haüy has placed the following remarks before this paragraph.

In the hypothesis we have adopted, caloric is considered as a very subtile and eminently elastic fluid, that penetrates all bodies, in the interior of which it is diffused more or less abundantly. The quantity of this fluid which a body contains, does not exert all its expansive force, but retains a more or less considerable part, in virtue of which the caloric makes an effort to escape from that body, in such manner that it can only be kept therein by the resistance of the caloric engaged in the surrounding bodies, and which has an equal tendency to escape. If this equality ceases, by a superabundance of caloric in some one of the bodies, it will yield a part of its fluid to the others, until the equilibrium is reestablished. The tendency of caloric to escape thus from a body, has been denoted by the word *tension,* which assimilates the state of caloric to that of a bent spring. It is properly in the quantity of this tension that what is denominated the *temperature* of a body consists; and according as the tension augments or diminishes, the temperature rises or falls; or, as it is likewise expressed in more familiar language, the body is heated or cooled.

Pa. 112, par. 123. M. Haüy has now enlarged this part of his work, by an account of the most important experiments of Count Rumford and Mr. Leslie relative to the reflection of caloric: but as the Translator has already adverted to this topic in note *o*, he trusts he need not go farther into detail here.

Pa. 129, line 16 from *b*: for—takes away; read—take away. Line 13 and 12 from *b*: for—yields some of its; read—yield some of their.

Pa. 132, line 14 and 15: for—$\frac{1}{3000}$; read—$\frac{1}{5000}$.

Pa. 136, line 3 from *b*: for—this distance; read—this distance of time.

Pa. 143, par. 166: for—In the words; read—in the works.

Pa. 150, note *z*. The Translator ought to have added to this note, that our learned countryman Mr. Henry Cavendish is the real discoverer of the composition of water. In the summer 1781 he set fire to 500,000 grain measures of hydrogen gas, mixed with about 2½ times that quantity of common air. By this process he obtained 135 grains of pure water. He also exploded 19,500 grain measures of oxygen gass, with 37,000 of hydrogen gas, and obtained 30 grains of water, containing in it a little nitric variety of theorems now demonstrated by this philosopher, are the following:

1. If we conceive any kind of prismatic tube, in a vertical position, with its inferior extremity immersed in a fluid of indeterminate quantity, the volume of fluid within, raised above the level by capillary action, is equal to the circumference of the interior base of the prism, multiplied by a constant quantity, which is the same for all prismatic tubes of the same matter immersed in the same fluid.

2. If the indefinite vessel in which the parallelopiped is immersed, include any number of fluids placed horizontally one above another; the excess of the weights of these fluids contained in the tube, over the weight of the fluids which it would have contained without capillary action, is the same as the weight of the fluid that would rise above the level, if the vessel contained only that fluid in which the inferior extremity of the parallelopiped is immersed.

3. If the vessel contain but two fluids, in which the prism is entirely immersed, so that its superior part is in one fluid, and its inferior in the other; the weight of the lower fluid, raised in the prism by capillary action above its level in the vessel, will be equal to the weight of a similar volume of the upper fluid, *plus* the weight of the inferior fluid, that would rise in the prism above the level, if there were no other fluid in the vessel, *minus* the weight of the superior fluid, that would rise in the same prism above the level, if the vessel contained this fluid only.

In the preceding theorems the base of the prism is supposed horizontal: but it is easy to conclude generally, that, whatever be the figure of the base of the prism, its vertical attraction, and that of the exterior fluid on the fluid included in it, are the same as if the base were horizontal. The first theorem therefore will hold generally, if we understand by the circumference of the interior base that of the interior section, perpendicular to the sides of the prism.

4. If the prism, the lower part of which is immersed in a fluid in a vessel of indefinite size, be inclined to the horizon, the volume of fluid in the prism, multiplied by the sine of the angle of inclination between the side of the prism and the horizon, will be constantly the same, whatever that inclination may be.

Pa. 233, line 1 of the note: for—commencin; read—commencing.

Pa. 253, par. 278. A curious fact, stated by Haüy in his second edition, proves how considerable is the quantity of caloric of which the air is deprived when its volume is contracted. A small piece of amadou is placed within the inferior extremity of the tube of a condensing-pump which serves to compress the air: the piston is then depressed as speedily as possible, and the heat which is developed by the condensation of the air is so active, that the amadou takes fire. If the body of the pump is terminated by a moveable bottom made of a piece of steel strongly screwed on, at the centre of which is adapted a glass lens through which the interior may be observed, there may be seen, at the first stroke of the piston, a lively and brilliant stream of light spouting in the midst of the condensed air.

It is known that the combustion of oxygen and hydrogen gas, produced by the electric spark, occasions the composition of water. The celebrated Biot has announced (*Magas Encyclop.* Avril, 1805) that the effect of a very rapid compression might be substituted for that of electricity, by giving place to the disengagement of an abundant quantity of caloric, which being restrained from dissipating all at once, would transmit its action to the gases, whose temperature it would sufficiently elevate to produce their inflammation. Though M. Biot thought it useless to verify immediately an assertion so closely connected with known observations; yet the experiment itself excited so great an interest, that to indicate it was to contract the engagement to perform it. He made use of an air-gun, whose bottom was closed by a very thin piece of glass: having introduced a mixture of the two gases into this gun, he gave a stroke to the piston; immediately there appeared a very vivid light, accompanied by a violent detonation which was a certain index of the combination of the gases. This experiment, however, requires precautions to prevent the dangers to which those who make it are exposed.

ADDENDA ET CORRIGENDA.

VOL. II.

PA. 35, art. 510. M. Haüy introduces the subject of *Secondary Piles* into this part of the new edition of his Work, as the Translator has into note *a*. But the following circumstance now mentioned by the Author, had not before fallen under the Translator's notice.

Among the various experiments whose results are analogous to those of the secondary pile, and which had been made previously to its invention, we shall confine ourselves to the mention of one due to Volta. This philosopher having put the two extremities of a slip of paper moistened with pure water, in communication with those of an ordinary pile, remarked that each of its two halves had acquired the species of electricity which resided in the corresponding pole of the pile, and that the electric density diminished on both sides as it approached the middle of the paper, where it had a neutral point. This slip has been denominated *Volta's riband.* It is easy to see that the conservation of the double electricity it exhibited, at least during an instant, depended upon the imperfection of the conducting faculty, either in the paper or in the water it had imbibed. We know even that the effect in question may obtain still, with due precautions, with respect to substances much more susceptible than paper and water of transmitting the two electric fluids. For as there is no body which possesses the conducting faculty in an absolute degree, the journey of the two fluids along the surface is always more or less progressive; and thus, however slight the resistance which the bodies oppose to the motion of these fluids, their density may be so small, that this resistance shall become capable of balancing their tendency to reunite, and of retarding, for an appreciable time, the return of the body to the natural state.

Pa. 52, line 10 from *b*: for—527; read—529.
Pa. 86, in the note: for—he re; read—here.

Pa. 107, note *k*. According to Mr. Gilpin's Observations on the Variation &c. of the Magnetic needle, published in part ii. of the *Philosophical*

Transactions for 1806, the declination taken in the month of July from 1790 downwards is as below.

1790	23° 39′ 0	1798	24° 0′ 0
1791	23 36 7	1799	24 1 8
1792	. . . .	1800	24 3 0
1793	23 50 5	1801	24 4 1
1794	23 54 4	1802	24 6 0
1795	23 57 1	1803	24 7 9
1796	23 59 2	1804	24 8 4
1797	24 0 3	1805	24 7 8

Hence, with regard to the annual increase of declination, Mr. Gilpin's observations strongly indicate that it is approaching a limit; and, in like manner, some observations at Paris favour a similar conclusion: for, in that city, from 1792 to 1794, the declination appeared fixed at 21° 54′ W; in 1798 it was 22° 15′; in 1799, 22° 0′; in 1800, 22° 12′; in 1801, 22° 1′; in 1802, 21° 45′; in 1803, 21° 59′; in 1804, 22° 15′, being for a period of twelve years, sometimes stationary, at others retrograde, as it oscillating about a limit. Thus also, its movements have been nearly the same at Geneva; where in 1800 the declination was 21° 29′, and in 1804, 21° 13′. So again, many naval officers are of opinion that in the western parts of the English channel, the declination has never reached 25°, and has already begun to decrease. While, on the contrary, Mr. Harding asserts that, at Dublin, the change in declination has been uniformly about 12′ 20″ annually from 1657, when there was no declination either at London or Dublin, till May, 1791, when it was 27° 23′ W. What the declination is now at Dublin we know not; though it is a datum we should be very glad to possess, that we might see how far it also indicated an approach to a limit westward.

of brass. He had a very handsome compass-box made of pure brass, as far as he could judge: the needle being taken out, placed on a pin fixed properly in a board, and clear of all other magnetics, the box attracted the needle at half an inch distance; and if suffered to touch, drew it full 90 degrees from the north or south points. He thought those parts of the box which were marked north and south attracted the strongest. Pieces of brass without any magnetic power, being properly hammered, and having given to them the double touch agreeably to Mr. Mitchell's method, were thus made to attract and repel the needle, as a magnet does, having two regular poles. Mr. Arderon likewise attempted to infuse the magnetic virtue into pewter; but he only succeeded so far as to cause the needle to tremble when a piece of such pewter was presented to it. See *Phil. Trans.* for 1758, or *New Abridgment*, vol. xi, pa. 285.

Pa. 139, line 12: for—forces; read—surfaces.
Pa. 154, lines 1 and 5 of the note: for—meridian; read—south.
Pa. 173, line 2 of the note: for—reflection; read—refraction.

Pa. 184, note *s*. The author has now given the results of M.M. Biot and Arrago, on the analogy between the refractive power of bodies and their chemical composition; results the principal of which the Translator has stated in the note just mentioned. It may, however, be proper to add in this place the formula M. Haüy has now inserted from Biot, by means of which that philosopher determines the ponderating quantity of any constituent in a proposed compound. Let P be the refractive power of a molecule of the mixture, A that of a particle of one of its principles, B that of a particle of the other principle, x the required ponderating quantity, and which we shall suppose to be that of the principle A; we shall have $xA + B(1 - x) = P$, whence we deduce $x = \frac{P - B}{A - B}$. Thus, the refractive power of a particle of hydrogen is 6·4534, that of a particle of air being the unit, the refractive power of a particle of azote referred to the same unit is 1·0297, and that of a particle of ammoniacal gas is 2·0874. From these data may be determined the ponderating quantity of hydrogen comprised in a weight of ammoniacal gas represented by unity. Pursuant to the formula, if we divide 2.0874 — 1.0297 by 6·4534 — 1·0297, we shall have 0·1950 for the ponderating quantity of hydrogen contained in the unit of ammoniacal gas. Now the experiments of Bertholet and Davy give $\frac{1}{5}$ or ·200, differing from the preceding result only by ·005; and even this difference may probably be imputed to the circumstance that the hydrogen gas employed by Biot and Arrago was, by reason of its great purity, $13\frac{1}{2}$

times lighter than the atmospheric air, which might augment its refractive power relative to the density.

Pa. 243, line 2 from *b:* for—sits; read—fits.

Pa. 253. The author here introduces into the new edition of his treatise, Scherffer's theory of *accidental colours,* mentioned in note *f,* pa. 287, and then adds—We have given the rule to which the sensation conforms that is produced upon the organ of sight. But what is the cause which occasions in the organ itself a disposition to conform to this rule? and how is it that a little white band placed, for example, on a red ground, though it transmits to the eye all the rays which compose its whiteness, excites there the impression of a greenish blue, that is to say of the colour which would be really presented by that little band, if we had subtracted from the whiteness the part of it which is common with the colour of the ground?

Scherffer has attempted to explain this illusion from the principle, that if a sense should receive at once two impressions of the same kind, one strong and vivid, the other much weaker, the latter would be as it were partly absorbed by the former, so that it would become imperceptible to us. Thus, to recur to the example of a little white band placed upon a red paper. The whiteness of this band may be considered as being composed of a blueish green and of red. But the sensation of the red colour acting with much less force than that of the surrounding colour of the same kind, is eclipsed by the latter, in such manner that the eye is only sensible to the impression of the green colour, which being foreign and distinct from the colour of the ground, acts upon the organ with all its energy.

Pa. 257, par. 747. The following is added from the new edition.

Mr. Leslie has recently undertaken the same experiments, making use of a very sensible instrument which he calls a *Photometer*, and whose construction approximates to that of the differential thermometer (par. 167, note *x*) previously employed by the same philosopher to observe the effects of radiant caloric (par. 125, note *o*). The essential part of the photometer consists also of a glass tube like a reversed syphon, whose two branches should be equal in height, and terminated by balls of equal diameter. But here one of the balls is of black enamel, while the other is of common glass. The motions of the liquor, which is here also sulphuric acid tinged red with carmine, are measured by means of a graduation the zero of which is situated towards the top of the branch that is terminated by the enamelled ball.

The use of this instrument is founded upon the principle, that when the light is absorbed by a body, it produces a heat proportional to the quantity of absorption. When the instrument is exposed to the solar rays, those rays that are absorped by the dark colour, heat the interior air, which causes the liquor to descend at first with rapidity in the corresponding branch. But as a part of the heat which had introduced itself by means of the absorption is dissipated by the radiation, and as the difference between the quantity of heat lost and that of the heat acquired goes on diminishing, there will be a point where these two quantities having become equal, the instrument will be stationary; and the intensity of the incident light is then estimated by the number of degrees which the liquor has run over.

The author of this ingenious instrument has pointed out its advantages in determining the progressive augmentation undergone by the intensity of the light, and the gradation in a contrary sense which succeeds to that progress, both from the beginning of the day to its end, and from the winter solstice to the end of the succeeding autumn. With the help of such an instrument one might also compare the action of rays of light in different countries, of which some dart with sufficient constancy from a fine and serene sky, while others seem to be covered with a veil which dims and obscures their lustre.

Mr. Leslie having proposed to himself, as we have said, to measure the energy of the diversely coloured rays which compose the solar spectrum, caused a beam of light to pass through a prism of flint glass; and the indications of the photometer presented successively to the different parts of the spectrum, have furnished nearly for the relation between the degrees of force of the blue, green, yellow, and red, rays, that of the numbers 1, 4, 9, 16; a relation which, considered in the two extreme terms, is double that which M. Rochon had deduced from his experiments, and more than quadruple that which was substituted for it by Dr. Herschel.

Pa. 383, par. 900. The subject of Micrometers is so nearly connected with those of Microscopes and Telescopes, that this part of the treatise can scarcely be reckoned complete without touching upon it.

A micrometer is an instrument by the help of which the apparent magnitudes of objects viewed though telescopes or microscopes are measured with great exactness, or by which the distances of remote objects may be ascertained.

Instruments of this kind may be divided into two classes, those which have not, and those which have, some movement amongst their parts. The micrometers of the former kind consist mostly of fine wires or hairs variously disposed, and situated within the telescope, just where the image of the object is formed. In order to determine an angle with these micrometers, much calculation is generally required. The micrometers of the other sort, of which there is a great variety, some being made with moveable parallel wires, others with prisms, others again with a combination of lenses, are more or less subject to several inconveniences: as, 1. Their motions generally depend upon the action of a screw; and of course the imperfections of its threads, and the greater or less quantity of lost motion, which is observable in moving a screw, especially when small, occasion a considerable error in the mensuration of angles. 2. Their complication and bulk render them difficult of application to a variety of telescopes, especially to the pocket ones. 3. They do not measure the angle without some loss of time, which is necessary to turn the screw, or to move some other mechanism. 4. They are expensive.

With a view to obviate most of these inconveniences, Mr. Cavallo invented a very simple micrometer; it consists of a small semi-transparent scale or slip of mother-of-pearl, about the twentieth part of an inch broad, and of the thickness of common writing paper: this slip is divided by means of parallel lines into a number of equal parts. Such micrometer is situated within the tube at the focus of the eye-lens of the telescope, where the image of the object is formed, and with its divided edge passing through the centre of the field of view. It is to be fixed upon the diaphragm, which generally stands within the tube at the focus of the eye-lens. Now, by looking through the telescope, the image of the object and the micrometer will appear to coincide: hence the observer may easily see how many divisions of the latter measure the length and breadth of the former; and, knowing the value of the divisions of the micrometer, he may easily determine the angle which is subtended by the object,—whence he can ascertain the magnitude of an object at a known distance, or the distance of an object of known magnitude, or the distance of an object of unknown magnitude by means of the angles it subtends at two known stations. See *Phil. Trans.* vol. 81. But this micrometer, however ingenious, requires some care in the adjustment of the slip of mother-of-pearl, and particularly in regulating its situation to suit different eyes.

Mr. David Brewster has lately directed his attention to the improvement of micrometers, and has invented one in particular which appears to be highly deserving of notice in this place. In this instrument a pair of *fixed* wires is made to subtend different angles by varying the magnifying power of the telescope, by sliding one tube within another; whereas in all other micrometers with wires this effect is produced by mechanical contrivances. Mr. Brewster's method of shutting and opening the wires optically is therefore free from all those sources of error to which other micrometers are subject, and renders it particularly useful to the practical astronomer; while the mode of changing the magnifying power by the motion of a second object-glass affords a length of scale equal to the focal distance of the principal object-glass. The same principle is peculiarly applicable to the Gregorian telescope; for the magnifying power of this instrument can be changed by merely increasing or diminishing the distance of the eye-piece from the large speculum.

In the common micrometer, which can manifestly, as well as Mr. Cavallo's and Mr. Brewster's, be used in the mensuration of distances, the focal length of the telescope to which it is attached remains always the same; so that a correction computed from an optical theorem must be applied to every angle that is measured: but in Mr. Brewster's telescope and micrometer, the focal length varies in the same proportion as the distance of the object; and consequently no correction of the angles can be necessary. To obviate the necessity of having a stand for the instrument, which would prevent its usefulness at sea, Mr. Brewster divides the second or moveable object-glass into two, as in the divided object-glass micrometer. By this contrivance two images are formed, and these images are separated or made to form different angles at the eye, by bringing the moveable object-glass nearer to the fixed one. In determining the angle, therefore, we have only to bring the two images of the object into contact; and such contact the eye is capable of ascertaining even during the agitation of a carriage, as the two images retain the same relative position whatever be their absolute motion.

This ingenious instrument, being formed with sliding tubes, is very portable and convenient; and will be found extremely useful to military gentlemen, and others who may wish to ascertain distances without a more cumbersome apparatus.

FINIS.

The following Works, lately published by Mr. Gregory, are sold at Mr. Kearsley's, N° 46, Fleet-street.

1. LESSONS, ASTRONOMICAL AND PHILOSOPHICAL, for the Amusement and Instruction of British Youth. A popular School-book: 3d edition, in 12mo, price 4s. in boards.

2. A TREATISE ON ASTRONOMY, in which the Elements of the Science are deduced in a natural Order from the Appearances of the Heavens to an Observer on the Earth; demonstrated on mathematical Principles, and explained by an Application to the various Phenomena. One large 8vo. volume, with 9 folding-plates, price 15s. in boards.

3. A TREATISE OF MECHANICS, THEORETICAL, PRACTICAL, AND DESCRIPTIVE. In two large 8vo. volumes, besides a volume containing 55 quarto plates. The first volume is devoted to the theory of Statics, Dynamics, Hydrostatics, Hydrodynamics, and Pneumatics: the second

Pl. IX.

Fig. 55.

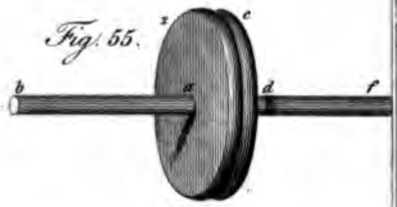


Fig. 57.

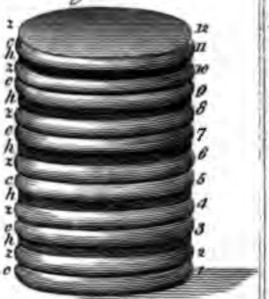


Fig. 60.

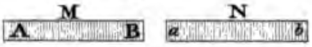


Fig. 61.

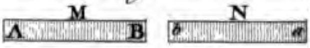
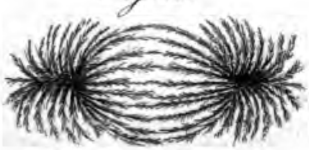


Fig. 62.



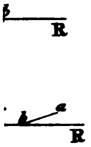


Fig. 63.

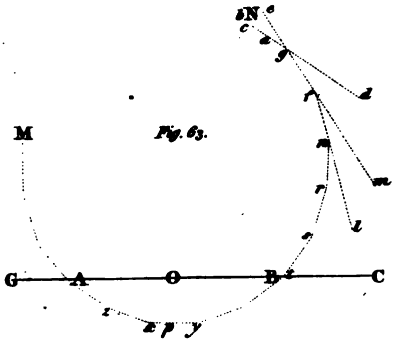


Fig. 66.

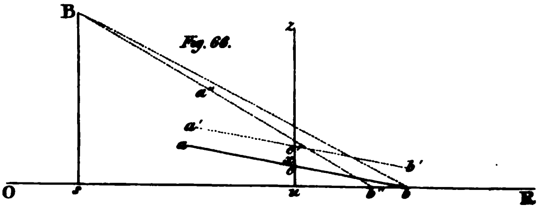


Fig. 67.

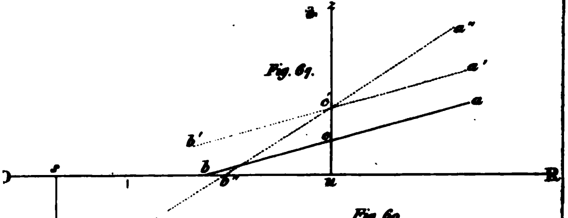


Fig. 69.

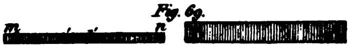


Fig. 70.

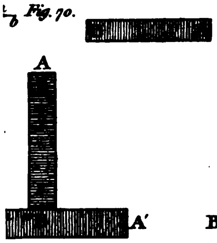


Fig. 71.

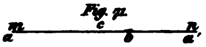
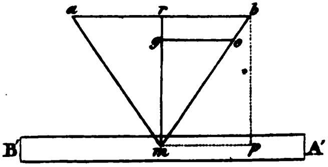


Fig. 73.



Barlow sculp.

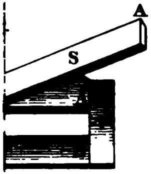


Fig. 74.

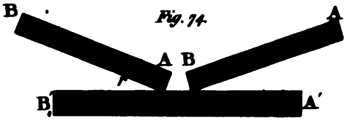


Fig. 76.

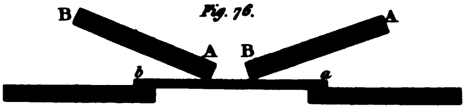


Fig. 78.

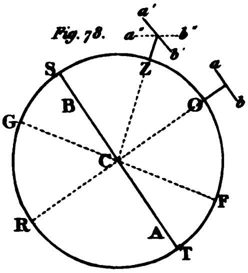
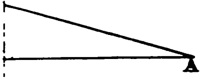


Fig. 79.



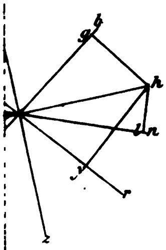
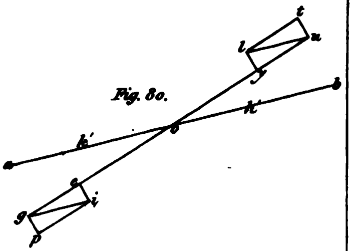


Fig. 80.



Basire sculp.

84.

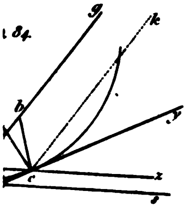


Fig. 83.

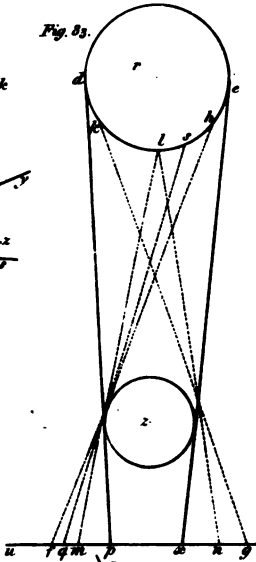
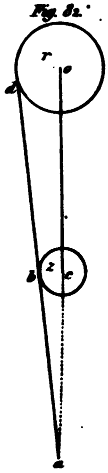
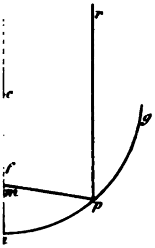


Fig. 82.



85.



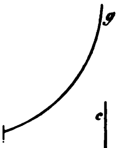


Fig. 87.

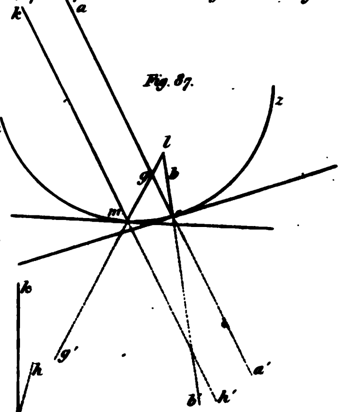
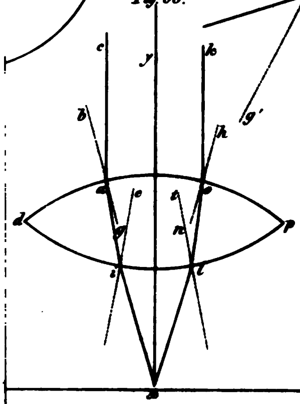
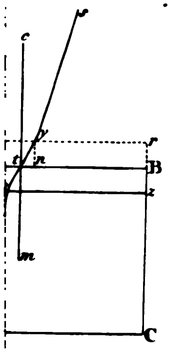


Fig. 88.



Barlow sculp.

Pl. XIII



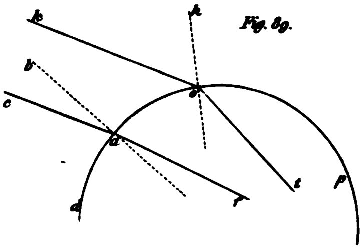


Fig. 89.

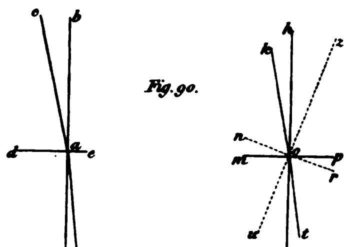


Fig. 90.

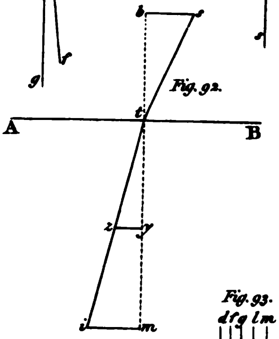
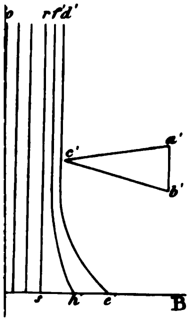


Fig. 92.

Fig. 94.



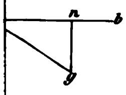


Fig. I.

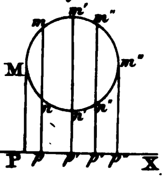
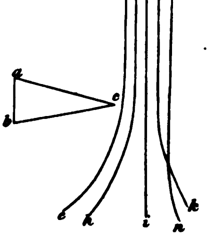


Fig. 93.



Barlow sculp

Fig. 97.

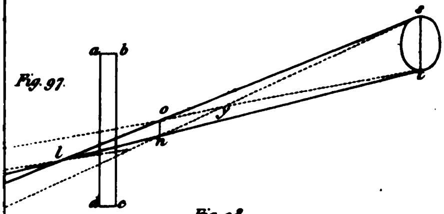


Fig. 98.

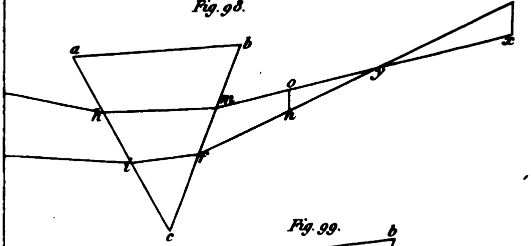
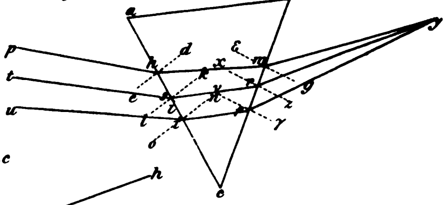


Fig. 99.



ig. 96

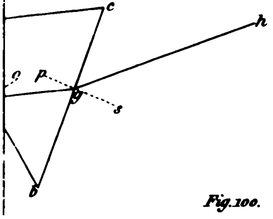
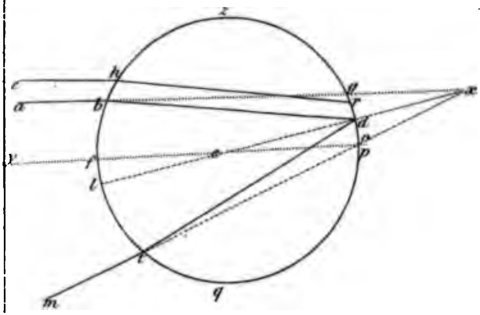


Fig. 100.



Basire sculp.

Pl. XX.

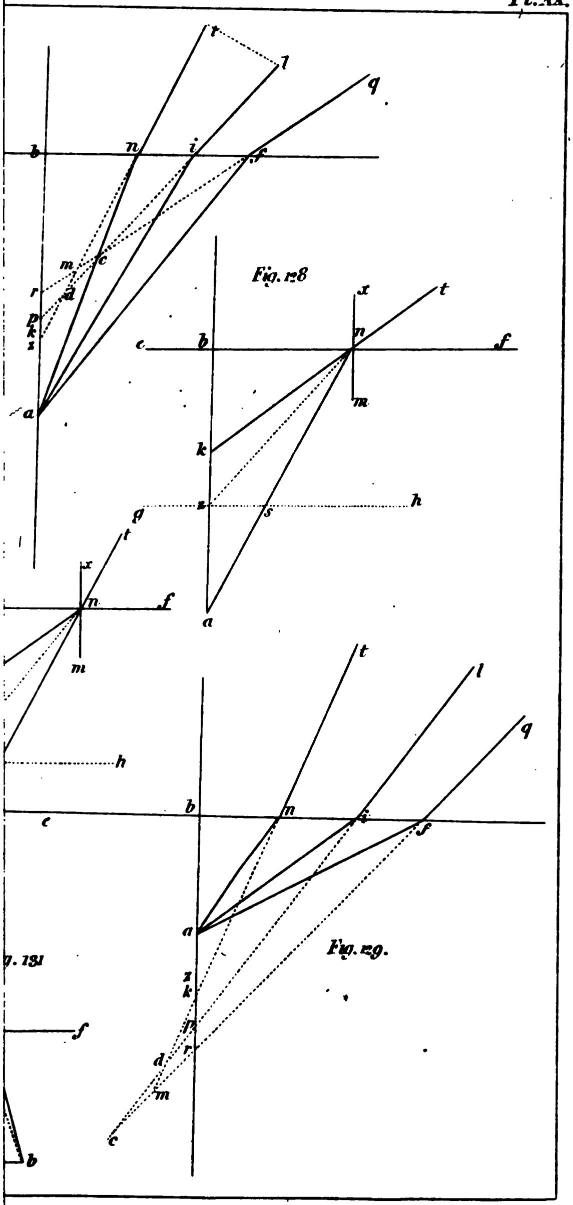
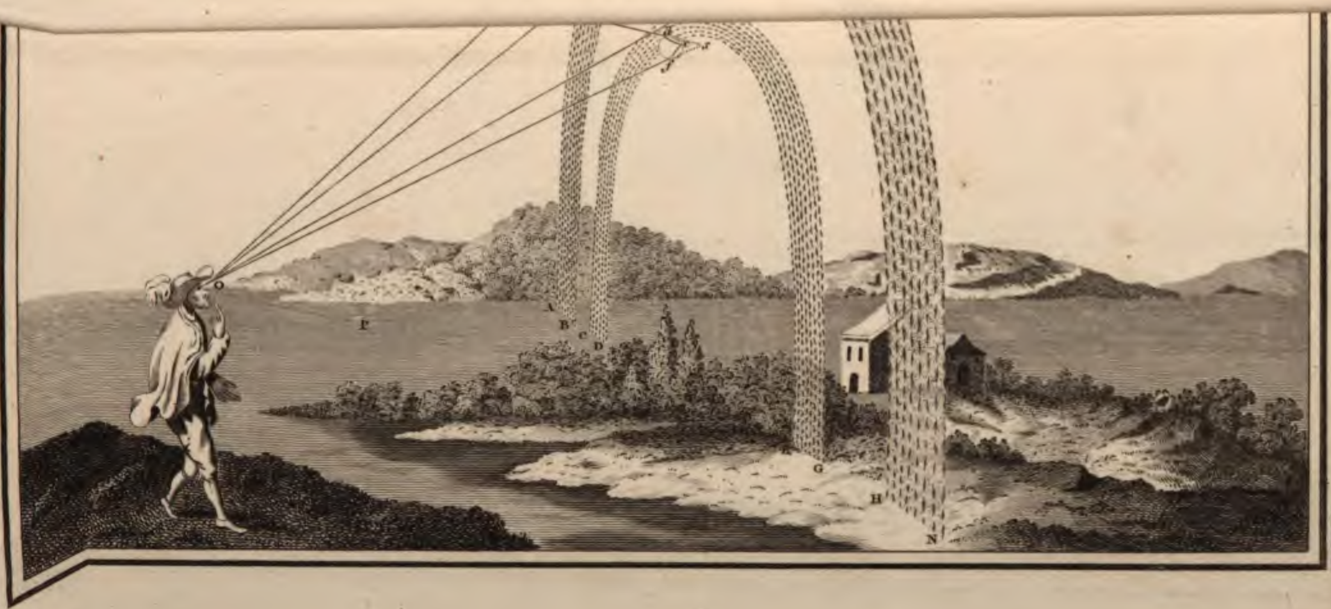


Fig. 128

Fig. 129.

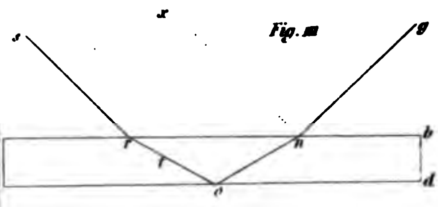
g. 131



Pl. XVI.

Pl. XVII

Fig. 111



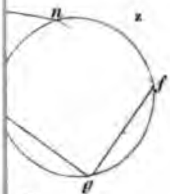
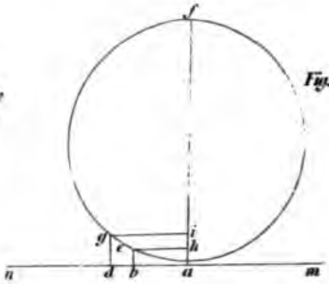


Fig. 108



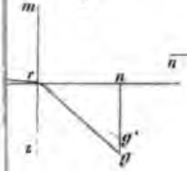
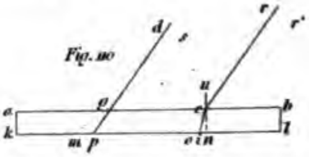


Fig. 110



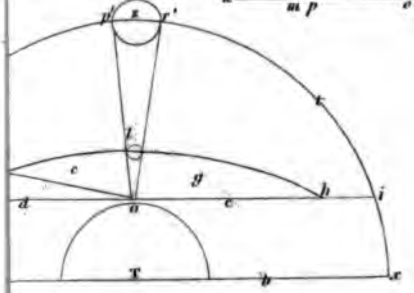
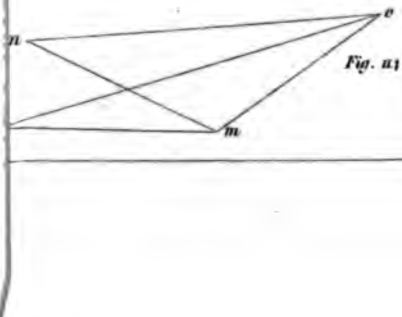


Fig. 113



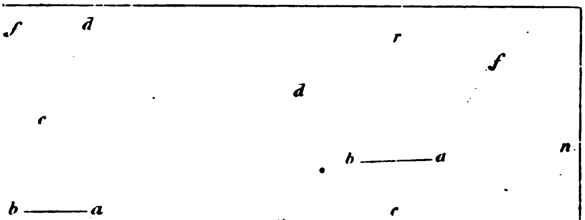
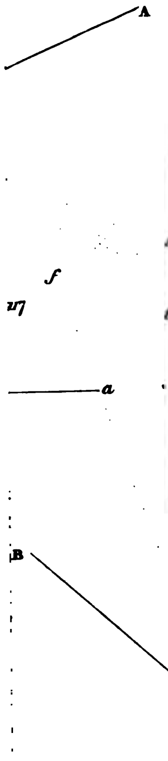


Fig. 116



117

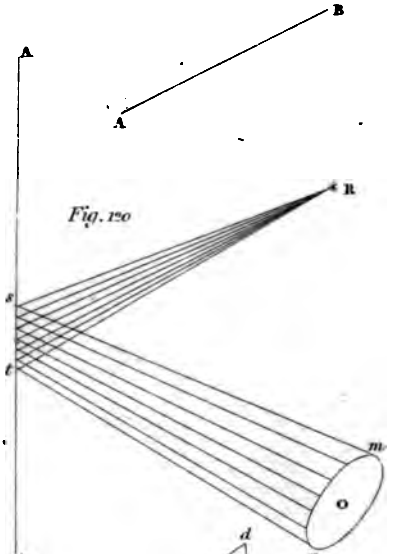


Fig. 120

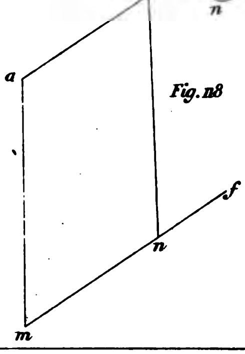
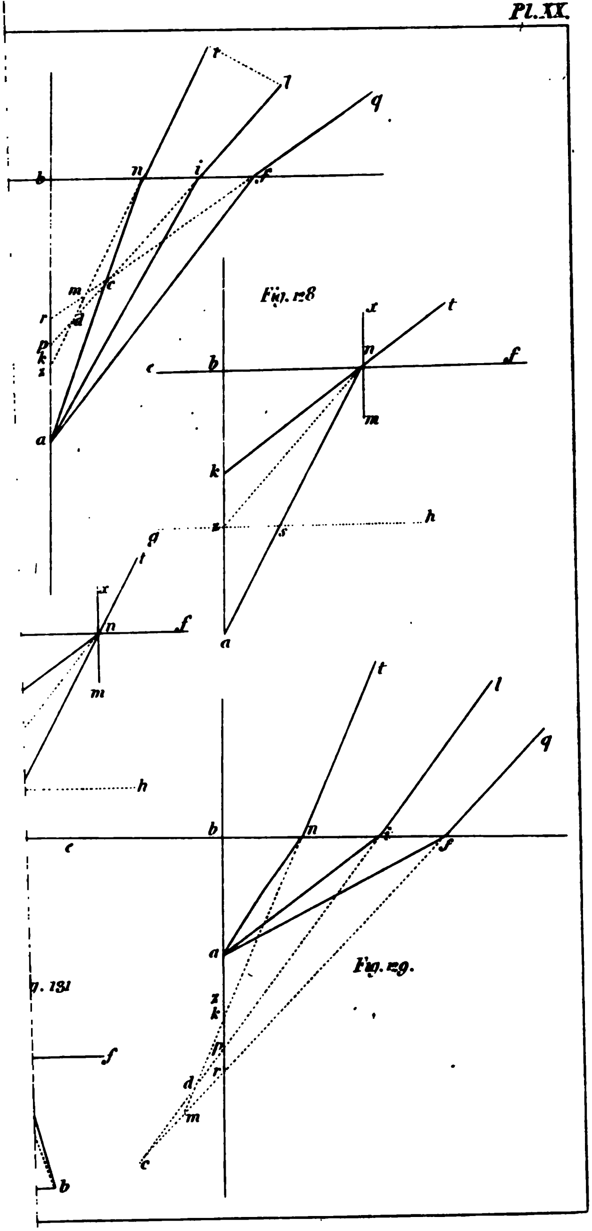
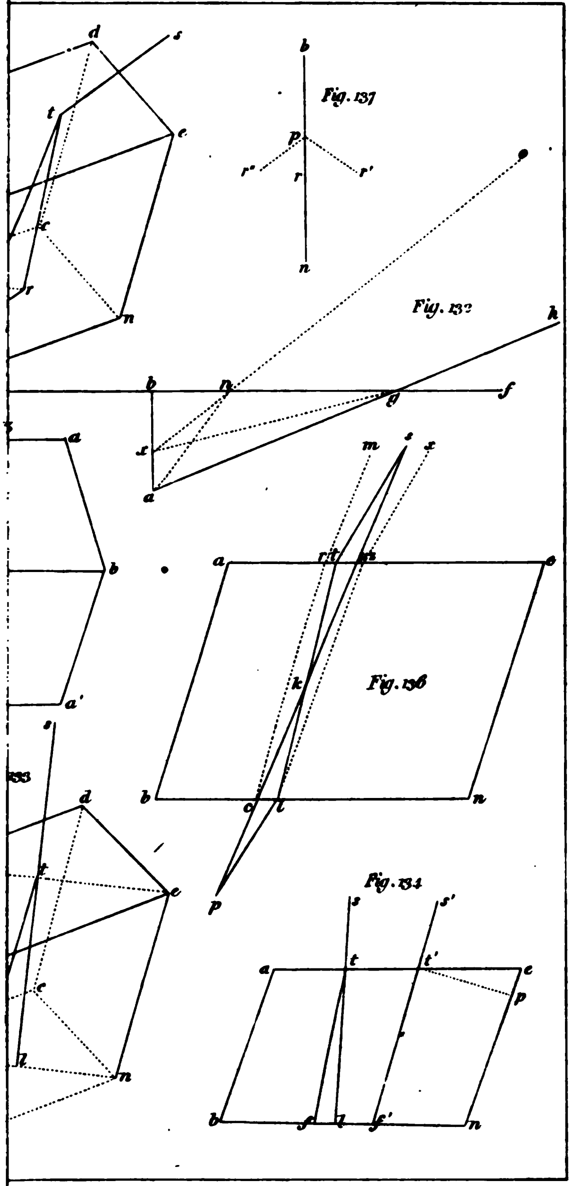


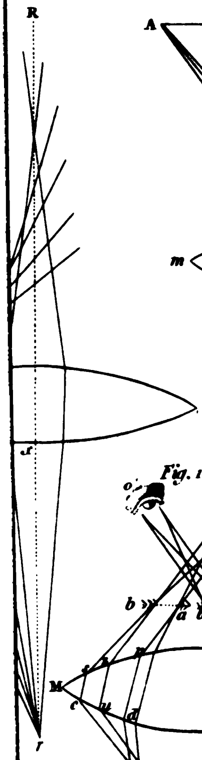
Fig. 118

Pl. XX.



t
l
q
b
n
i
f
m
c
r
d
p
k
z
a
Fig. 128
x
t
c
b
n
f
m
k
z
s
h
a
g
t
x
n
f
m
h
t
l
q
b
n
i
f
c
a
Fig. 129.
z
k
p
r
d
m
c
g. 131
f
b


d
s
t
e
x
r
n
b
p
r''
r
r'
n
Fig. 137
Fig. 132
k
b
n
g
f
x
a
a
b
a'
m
s
x
a
r
t
m
e
k
Fig. 136
b
o
l
n
s
33
d
t
e
c
l
n
p
Fig. 134
s
s'
a
t
t'
e
p
b
f
l
f'
n



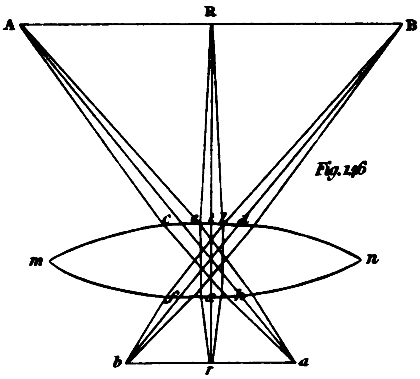


Fig. 146

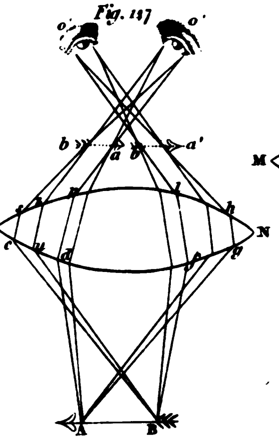


Fig. 147

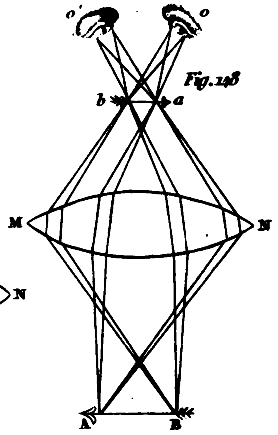


Fig. 148

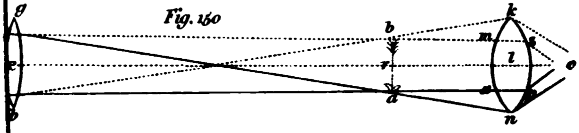


Fig. 160

Fig. 155

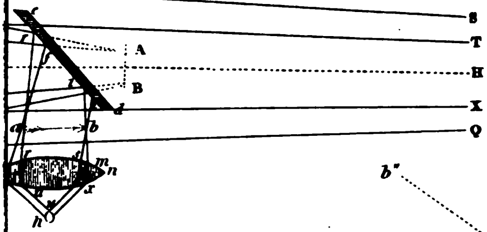


Fig. 157

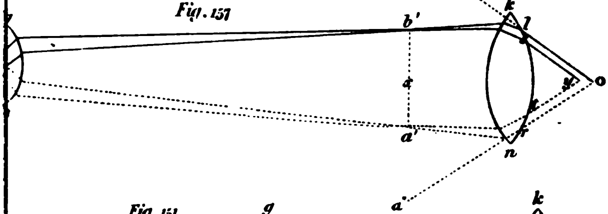


Fig. 151

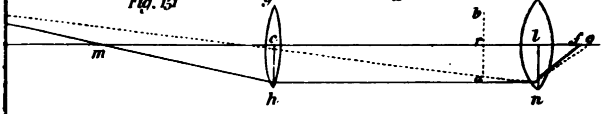


Fig. 153

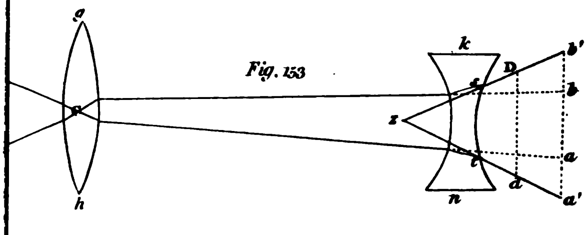


Fig. 156

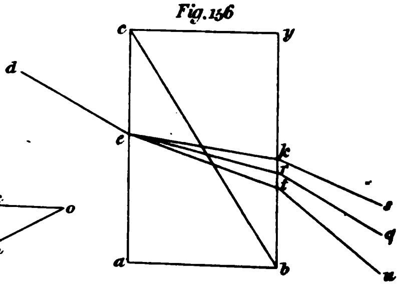


Fig. 152